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Wind Erosion of Biochar-Amended Soil – A Wind Tunnel Experiment

Erosão de Solo com Biochar – Um Estudo em Túnel de Vento

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Dissertation presented to University of Aveiro for fulfillment of the necessary requirements to the obtainment of the degree in Master of Sciences in Environmental Engineering, under the scientific guidance of Professor Doutor Carlos Alberto Diogo Soares Borrego, Full Professor from the Department of Environment and Planning of University of Aveiro, and co-guidance of Doutor Franciscus Verheijen and Doutor Jorge Humberto Amorim, Post-Doctoral Researchers of Department of Environment and Planning of University of Aveiro

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Dedico este trabalho à minha família e namorada, por tudo.

O júri

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Keywords Biochar, wind erosion, wind tunnel, soil management

Abstract

Biochar application to soils has been reported in the scientific community as a possible means of improving agricultural productivity and, at the same time, as a powerful tool for carbon sequestration and climate change mitigation. However, current knowledge of biochar effects on soil functions and possible environmental threats is still not enough for a full-scale implementation. Erosion is one of the most serious and irreversible threats to soil and there is still no information if biochar may increase or decrease soil erosion rates. Soil erosion by wind is of particular interest for biochar, because of the low particle density and potential human exposure. The purpose of this study was to fill this knowledge gap by investigating the wind erosion potential of biochar-amended soil with a focus on the effect of soil moisture content, using a laboratory wind tunnel.

Firstly, experimental tests were implemented in the DAO wind tunnel to define a robust wind erosion methodology in a facility only used for smoke studies. Sediment collecting methods, dust fraction analysis and wind velocity range were the main factors that required investigation. The erosion of biochar-amended soil (10% m m^{-1}) and control soil (sandy soil) was simulated by positioning a tray divided in a sample area and an area for creeping particles, inside the test section of the wind tunnel. To determine the effect of soil moisture content on the erosion potential, four moisture contents were used: 0.2%, 1.7%, 4% and 8% (gravimetric). The wind tunnel simulations were performed with the duration of 15 minutes at a wind velocity of 7 m s^{-1}. The samples of collected sediment were oven-dried and weighed to give the sediment loss as consequence of the erosion event.

Results on the erosion simulations for control and biochar-amended soil with the wind flow velocity of 7 m s^{-1} (small erosion event) indicated that only biochar particles were displaced. Erosion of biochar-amended soil was similar for 0.2%, 1.7% and 4.0% and despite a sediment loss reduction of 50% from 4% MC to the higher MC, 8%, this latter was not identified as the threshold MC for the moment when erosion ceases to exist. As for mineral particles, after 4% MC there was no sediment collected indicating this MC as the threshold, even though a reduced mass of particles eroded for the smaller MCs. Further future tests are needed to build a more comprehensive understanding of wind erosion of biochar-amended soils. Relevant factors to include are: higher wind velocities representative of medium and high erosion events, as well as higher MCs to identify when erosion of biochar particles will stop completely. Secondly, based on the results found in the present study, other soil types and biochar types warrant further investigation. Studies like this contribute for the understanding of the effects of biochar application to soil functions, as well as the behaviour and fate of this material, which are indispensable for the development of adequate biochar regulations and policies.

Palavras-chave Biochar, erosão eólica, túnel de vento, gestão do solo

Resumo

A aplicação de biochar no solo tem sido referida na comunidade científica como um possível meio para melhorar a produtividade agrícola e, ao mesmo tempo, como um instrumento para sequestro de carbono e mitigação de alterações climáticas. Contudo, o conhecimento actual sobre os efeitos do biochar nas funções do solo e possíveis ameaças ambientais não é, ainda, suficiente para uma implementação em larga escala. A erosão é uma das mais sérias e irreversíveis ameaças ao solo e não existe, ainda, informação se o biochar pode aumentar ou reduzir os níveis de erosão. A erosão do solo pelo vento é de particular interesse para o biochar, devido à reduzida densidade das partículas e à potencial exposição humana. O objectivo deste trabalho foi preencher esta falha ao investigar o potencial de erosão do solo melhorado com biochar com enfoque no efeito do teor de humidade, usando um túnel de vento.

Primeiramente, testes experimentais foram implementados no túnel de vento do DAO para definir uma metodologia robusta de erosão eólica numa estrutura, até então, apenas usada para estudos de dispersão de poluentes. A colecta do sedimento, análise de fracção de poeiras e a gama de velocidades foram os factores principais que necessitaram de investigação. A erosão de solo com biochar (10% m m^{-1}) e de solo de controle (solo arenoso) foi simulada posicionando um tabuleiro dividido em área de amostra e área para partículas de rolamento, dentro da secção de teste do túnel de vento. Para determinar o efeito do teor de humidade do solo no potencial de erosão, quatro teores de humidade foram usados: 0.2%, 1.7%, 4% and 8% (gravimétricos). As simulações no túnel de vento foram realizadas com a duração de 15 minutos a uma velocidade do vento de 7 m s^{-1}. As amostras de sedimento colectado foram secas e pesadas para fornecerem a perda de sedimento como consequência do evento de erosão.

Os resultados das simulações de erosão para o controle e o solo melhorado com biochar, com a velocidade de 7 m s^{-1} (reduzido evento de erosão) indicaram que apenas partículas de biochar foram movidas. Erosão de solo com biochar foi semelhante para 0.2%, 1.7% and 4.0% e, apesar da redução da perda de sedimento em 50% do teor de 4% para para o teor mais alto, 8%, este último não foi identificado como sendo o limiar para o momento em que a erosão deixa de existir. Relativamente às partículas minerais, após o teor de 4% não houve sedimento colectado indicando este teor de humidade como o limiar, ainda que uma massa reduzida de partículas tenha sofrido erosão para teores mais reduzidos. Testes futuros são necessários para gerar um melhor conhecimento acerca de erosão de solo com biochar pelo vento. Factores relevantes a incluir são: maiores velocidades do vento, representativas de eventos de erosão médios e elevados, tal como maiores teores de humidade para identificar quando a erosão de partículas de biochar pára por completo. Em segundo lugar, com base nos resultados observados neste estudo, outro tipos de solo e biochar impõe mais investigação.Estudos como este contribuem para perceber os efeitos da aplicação de biochar nos solos, bem como o comportamento e destino deste material, que são indispensáveis para o desenvolvimento de regulamentos e políticas adequadas sobre biochar.

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List of abreviations

ANOVA	Analysis of Variance
CDR	Carbon Dioxide Removal
CEC	Cation Exchange Capacity
DAO	Departamento de Ambiente e Ordenamento
EC	Electrical Conductivity
GHG	Greenhouse Gas
HOC	Hydrophobic Organic Compounds
MC	Moisture Content
PAH	Polycyclic aromatic hydrocarbon
PIV	Particle Image Velocimetry
$PM_{2.5}$	Particulate matter with an aerodynamic diameter less than or equal to a nominal 2.5 micrometers
PM_{10}	Particulate matter with an aerodynamic diameter less than or equal to a nominal 10 micrometers
RWEQ	Revised Wind Erosion Equation
SOM	Soil Organic Matter
TFV	Threshold Friction Velocity
WEPS	Wind Erosion Prediction System
WEQ	Wind Erosion Equation

I GENERAL INTRODUCTION, RESEARCH AIMS AND RELEVANCE

1.1. Introduction

The importance of soil as a resource to the human population is undeniable. Although being indispensable to the continuation of human life on Earth, it may be seen by the average person as something of insignificant value. Soil serves as a supplier of such basic things as food, fuel and fiber and its perceived utility has changed from the traditional purpose of cultivating plants to having other functions related to environmental quality or global climate change (see Table 1).

Table 1. Multifunctionality of soils (adapted from BLANCO-CANQUI (2008)).

Food security, biodiversity and urbanization	Water quality	Projected global climate change	Production of biofuel feedstocks
• Food • Fiber • Housing • Recreation • Infrastructure • Waste disposal • Microbial diversity • Preservation of flora and fauna	• Filtration of pollutants • Purification of water • Retention of sediments and chemicals • Buffering and transformation of chemicals	• Sink of CO_2 and CH_4 • C sequestration of soil and biota • Reduction of nitrification • Deposition and burial of C-enriched sediment	• Bioenergy crops (e.g., warm season grasses and short-rotation woody crops) • Prairie grasses

Soil erosion is a natural process that has been changing the planet's physical appearance throughout time. It is defined as "the wearing away of the land surface by physical forces such as rainfall, flowing water, wind, ice, temperature change, gravity or other natural or anthropogenic agents that abrade, detach and remove soil or geological material from one point on the earth's surface to be deposited elsewhere" (HUBER et al., 2008). The term "accelerated soil erosion" is used for soil erosion rates above the "geological erosion" rates caused by anthropogenic activities, which may jeopardize the soil depuration capacity and compromise its functions (HUBER et al., 2008).

Accelerated soil erosion is intrinsically related to agriculture, and has been observed since the agricultural revolution, approximately 10,000 years ago (HOOKE, 2000, WILKINSON, 2005). In the last centuries, along with the expansion and development of agriculture came an increase in soil erosion, resulting in higher land degradation (LAL et al., 1990). To accurately study how this phenomenon influences economic and/or environmental aspects is complicated because the extent, magnitude and rate of soil erosion can vary greatly in space and time.

Certain agricultural activities (e.g., overgrazing, or land drainage) have contributed significantly to the increase in soil erosion rates, however, other factors also played a role on deteriorating this natural resource. Land development and land cover changes, urban pressure through increasing population density and needs for transportation routes, consumption of food and goods, tourism, climate change, they all act, individually or combined, as pressure-induced agents (CASTILLO et al., 2004).

Soil erosion in the United States agricultural fields has been estimated to cost around 40 billion dollars per year, including on-site and off-site costs, while in England and Wales estimates account for £205 million per year (PIMENTEL et al., 1995, URI, 2000, VERHEIJEN et al., 2009). The on-site effects refer to the reduction of cultivable soil depth, soil fertility and moisture, occurring in agricultural soils because of the decline in nutrients and organic matter available, changes in soil structure and the soil loss or redistribution within a field. The overall result is the reduction of agricultural field productivity which could increase the costs with fertilizers and/or more irrigation to maintain crop yield. The off-site effects are a consequence of sedimentation downstream or downwind, which is responsible for reducing the capacity of rivers and drainage ditches, increasing the chance of floods, causing problems for irrigation systems, etc. Also, surface water eutrophication and atmospheric CO_2 emission may occur as a result of sediment transport. Chemical compounds present in the sediments can promote the increase of nutrients in water bodies while the separation of aggregates exposes the organic matter and the subsequent decomposition of soil organic content releases CO_2 (MORGAN, 2009). According to LAL (1995), 1.14 Pg C are emitted to the atmosphere, each year, due to soil erosion, making land degradation an important issue when discussing climate change.

There is now much evidence suggesting that current mitigation strategies and related sustainable development practices are not sufficiently effective to combat greenhouse gases (GHGs) emissions (STOCKER et al., 2013). The quest to find new and more effective ways of reducing GHGs impacts led to the development of Carbon Dioxide Removal (CDR) methods that have been a focus of scientific research. CDR is the term given to a type of technology which is used to remove CO_2 directly from the atmosphere. It is a way of applying geoengineering techniques that may alleviate the impacts of climate change by either increasing natural sinks for carbon, or reducing the CO_2 concentration in the atmosphere. However, since these geoengineering options may affect all parts of the climate system, one cannot forget possible harmful outcomes that may arise from the use of these techniques (EDENHOFER et al., 2011).

CDR methods involve the ocean and/or land processes combined with technological knowledge. The land-based methods are divided in two groups: the ones that increase natural sinks, such as afforestation, and the others that reduce natural sources, where one can include biochar application to soils (EDENHOFER et al., 2011). Biochar application to soils may "divert a portion of the existing carbon flux that resides within managed ecosystems, or intercept enhanced net primary productivity production in the form of increased harvest or waste biomass" (SOHI et al., 2010). This material may be pyrolyzed and replaced in soil in a more stable form, being less available for degradation. This way, much less carbon is returned to the atmosphere from sites of decomposition (soil, landfill, etc) which also decreases associated emission from other GHGs (such as methane) (SOHI et al., 2010).

1.2. Biochar

1.2.1. Historical perspective

The discussion about using charred biomass as a soil amendment was initiated after the re-discovery of naturally infertile soils in the Amazon region that contained considerable amounts of human-induced char, as well as other organic and inorganic components, and that showed substantial improvements in fertility (GLASER et al., 2000, GLASER et al., 2001). Known as "Terra Preta" (Portuguese for "Dark Earths"), these man-made soils, obtained by adding fresh and charred biomass, as well as a range of other components, were intentionally made by native communities around 500 to 2500 years ago (LEHMANN & RONDON, 2006, NEVES, 2008).

Starting in the Pre-Colombian period, these Anthrosols maintained their higher fertility, for hundreds or thousands of years (CUNHA et al., 2009, FRASER et al., 2011). They are also characterized by increased nutrient availability when compared to typical Amazonian soils in other regions nearby (FRASER et al., 2011, LEHMANN et al., 2003). Developments on scientific research for "Terra Preta" soil has also "yielded important basic information on the functioning of soils, in general, and on effects of biochar, in particular" (LEHMANN & JOSEPH, 2009).

1.2.2. Definitions and concepts

Biomass can be transformed by a thermochemical process in a low or zero oxygen atmosphere (pyrolysis). In addition to the solid material produced, which is generally called char, CO_2 and some combustible gases (CO, CH_4 and H_2), volatile oils and tarry vapors are also produced (SOHI et al., 2010). In this way, biochar is defined as biomass-derived char produced specifically for application to soils in order to improve soil functions, e.g. productivity, C storage, or filtration of percolating soil water. Thus, the manufacture conditions and application purpose are key factors that distinguish biochar from other C-rich materials, such as charcoal, which is also obtained through pyrolysis but only from woody feedstocks and for energy purposes (LEHMANN & JOSEPH, 2009, SOHI et al., 2010).

When compared to charcoal, biochar represents a much wider group of materials whose properties may vary far more than the first. Biochar includes stabilized plant material where carbon (C) is stored mostly in a recalcitrant form that, consequently, will not suffer significant degradation by microorganisms or chemical reactions in the environment (LENTON & VAUGHAN, 2012). The residence times in soil (for wood biochar) are estimated to be in the range of hundreds to thousands of years. The fact this carbon is not easily degraded and converted to CO_2 through microbial activity, comparatively to natural organic matter (NOM) or other organic soil amendments, makes biochar a possible "instrument" for carbon mitigation strategies.

The improvement of agronomic yield with biochar application has been reported throughout the literature (BIEDERMAN & HARPOLE, 2013, GALINATO et al., 2011, JEFFERY et al., 2011, KOOKANA et al., 2011). However, there are also studies with no significant improvement of crop growth with a various range of soil/ biochar combinations (SPOKAS et al., 2012), and even studies where reductions in crop yield were observed (AGUILAR-CHÁVEZ et al., 2012, GASKIN et al., 2010) so it is important to gather more information about effects and mechanisms between biochar, soil and crops. The fact that, in biochar experiments, the material may stay in the soil between 1 week to a few years (considerably less than the biochar residence times which may go to 1000s of years) brings more uncertainties related to its application benefits for soil (MUKHERJEE et al., 2014). Biochar may also affect many different soil functions and ecosystem services and in an irreversible way, so more interdisciplinary research is needed before policy may be implemented (VERHEIJEN et al., 2010).

Although the majority of published studies have shown an increase in crop productivity, it should be noted that current knowledge is still not enough for a full-scale implementation (JEFFERY et al., 2011). Therefore, it is essential to continue to carefully investigate all interactions between biochar and soil, contributing to a better understanding of biochar's influence on ecosystem services (GURWICK et al., 2013, JEFFERY et al., 2011).

1.2.3. Production and material characteristics

The characteristics of the biochar as a material depend strongly on the type of processes involved in its production. Biochar is a solid product of pyrolysis, which is a thermochemical process that also yields a liquid and gaseous product, bio-oil and syngas (mostly CO, H_2, CH_4, CO_2, H_2O) respectively, from low-density biomass and other organic materials (LAIRD et al., 2009). In this process, temperatures generally above 300 ^{0}C, in a near oxigen-free environment contribute for the thermally decomposition of organic materials. Bio-oil appears as a result of the syngas cooling process where polar and high-molecular weight compounds condense out as liquid (LAIRD et al., 2009).

Pyrolysis may receive different designations for different process conditions and products originated. Conditions as temperature, heating rate and residence time have been shown to have a profound effect on the product yields and compositon (GRASSI et al., 1987). These thermochemical technologies may be classified into four general categouries: slow pyrolysis (see Figure 1), intermediate pyrolysis, fast pyrolysis and gasification (LAIRD et al., 2009). Conventional carbonization or slow pyrolysis present long vapor residence time and low heating rate as key parameters and have been used on charcoal production in the past (ZHANG et al., 2010). The equipments used in slow pyrolysis are either batch systems known as "charcoal kilns" or continuous systems that increase the temperature with a slow rate before reaching 400 ^{0}C (LAIRD et al., 2009, MANYA, 2012). Product yields for this process are 35% for both biochar and syngas (by mass) and 30% for bio-oil (GOYAL et al., 2008).

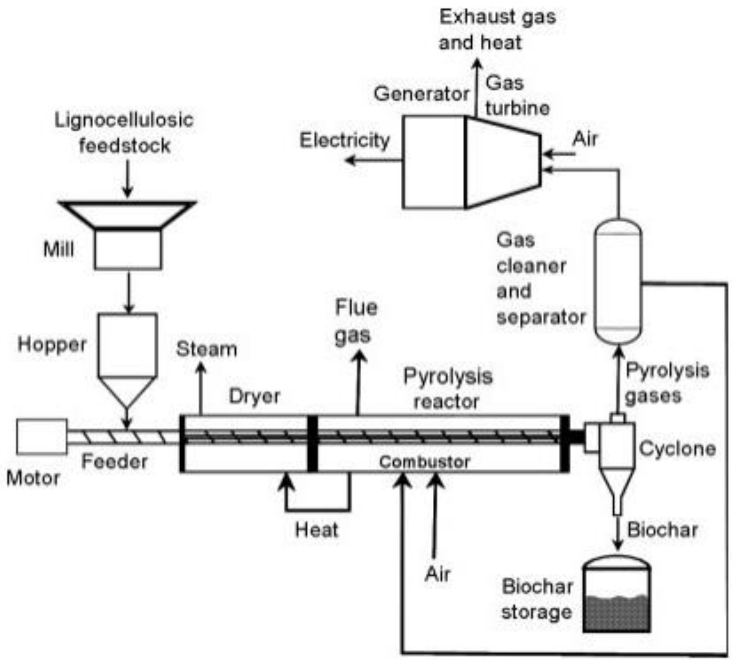

Figure 1. Example of system used for production of biochar through slow pyrolysis in a continuous, auger-based, slow pyrolyzer (adapted from LAIRD et al. (2009)).

In intermediate pyrolysis moderate temperatures and hot vapour residence times of 10-20 s lead to the formation of more liquid product in comparison with biochar and gas formation (VERHEIJEN et al., 2010). In fast pyrolysis bio-oil production is maximized in continuous flow systems where biomass is heated to temperatures > 400 ^{0}C with less than 1 s resident time, with typical yields of 50–70% bio-oil, 10–30% biochar, and 15–20% syngas by mass (LAIRD et al., 2009). Gasification, contrarely to fast pyrolysis, maximizes the production of syngas and if sufficiently high temperatures are obtained, a gasifier produces very little char or bio-oil (LAIRD et al., 2009).

Additionally to the conditions during the process of pyrolysis, the type of organic material that is pyrolyzed also influences greatly the products obtained in the end. A wide range of organic material may be used in the process, including “corn and wheat stover, forestry byproducts, urban yard wastes, industrial byproducts, animal manures and sewage sludge” (LAIRD et al., 2009). However, the yield of solid residue (char) relative to the liquid and gaseous phase along with the products physical and chemical characteristics may all be quite diverse depending on the input material (VERHEIJEN et al., 2010).

Biochar characteristics, both physically and chemically, may vary and its composition is far from being homogeneous. Biochar major components are carbon, volatile matter, minerals (ash) and moisture (SOHI et al., 2009). The properties from the feedstock that gives origin to the biochar influence the product characteristics after pyrolysis. Along with the type of feedstock (variable composition of hemicellulose, cellulose and lignin, mineral matter and water) the pyrolysis conditions particularly temperature, influence greatly the biochar, since they define the physical and chemical reactions by which the biomass goes through during biochar production (ANTAL & GRØNLI, 2003, DEMIRBAS, 2004).

The highly recalcitrant nature of biochar is closely related with the way C is present in the biochar structure. Total C content in biochar is usually high and it may account for 90% (weight) of the material's composition. In biochar, C is in the form of compacted graphene sheets with aromatic rings at the surface (ANTAL & GRØNLI, 2003, DEMIRBAS, 2004). Hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P) and sulphur (S) that were present in feedstock, prior to pyrolysis, are bonded to aromatic structure as functional groups (BOURKE et al., 2007). Biochar highly heterogeneous and reactive surface is a consequence of the functional groups which also define areas where properties may present oxidizing and reducing, acidic and basic, hydrophilic and hydrophobic conditions. Additional to these characteristics, volatilization of microelements during the process of pyrolysis produce an extensive porous network which contributes to biochar large surface area (DEMIRBAS, 2004).

1.2.4. Interactions with soils

Soil physical properties as structure, pore size distribution, bulk density and texture can all be influenced by the application of biochar. It has been already reported in the literature its ability to increase the overall surface area of the soil, therefore improving soil aeration and soil-water retention (CHAN et al., 2008, DOWNIE et al., 2009, KOLB et al., 2009). The improvement on soil surface area could also benefit the overall sorption capacity and microbiological activity (DOWNIE et. al, 2009).

The soil-water retention is determined by the distribution and connectivity of pores in the soil-matrix, which is largely regulated by soil particle size associated with soil aggregation and soil organic matter (SOM) content (VERHEIJEN et al., 2010). Biochar interacts with SOM, minerals and microbiological activity and, as a consequence, improves soil aggregation. Studies have shown increases in water holding capacity, but also in cation exchance capacity (CEC). GLASER et al. (2002) found an increase in water holding capacity of 18% for anthrosols (man-made tropical soils).

Biochar acts as binding agent due to the negative surface charges contributing to the material high CEC which is consistently higher than soil, clay, or soil organic matter (YUAN et al., 2011). The soil CEC indicates how well some nutrients (cations) may be bound to the soil and, by improving soils CEC, biochar may also contribute to increase nutrient bioavailability in the soil. Increases in nutrient retention may prevent leaching losses below the plants effective rooting zone, thus, increasing soil fertility and reducing the probability of acidification and other problems on the quality of surface and groundwater (LAIRD et al., 2010).

Stability of biochar in soil is a key parameter to understand its potential of sequestering CO_2. Indications from black carbon present in soils originated by anthropogenic activities range from several thousands to hundreds of years (VERHEIJEN et al., 2010). However these conditions are different than freshly made biochar which is not an inert material and may be oxidized under the influence of high temperatures and strong oxidants (CHENG et al., 2006). Over time, this may result in accumulation of carboxylic functionalities in the surface of biochar particles, depending on the biochar type and environment characteristics, and improved interactions between the material and other soil components, such as SOM (BRODOWSKI et al., 2005).

Hydrophobic organic compounds (HOCs) incorporation (such as PAHs and pesticides) in soil may be increased due to the application of biochar which can enhance soil sorption capacity (VERHEIJEN et al., 2010). This negative effect may be dependent of the chemical and structural properties of the contaminant as well as of the surface area or pore size distribution from biochar (ZHU et al., 2005). Biochar may also contribute for the reduction of the total N_2O emissions since it can increase the availability of N for denitrification (SOHI et al., 2009).

1.3. The study of soil erosion by wind

1.3.1. Definitions

Wind erosion is a severe problem around the world and the main cause for desertification, particularly in arid and semi-arid regions (LAL, 1994). Along with sub-humid areas these regions receive the designation of drylands which are susceptible to intense degradation, creating desert-like conditions (see Figure 2). They include almost 45% of all cultivated land and each year around 12 million hectares are lost because of drought and desertification (UNCCD, 2011). Also considered drylands, hyper-arid areas or deserts are not taken into account in the context of sustainable development (UNCCD, 2011).

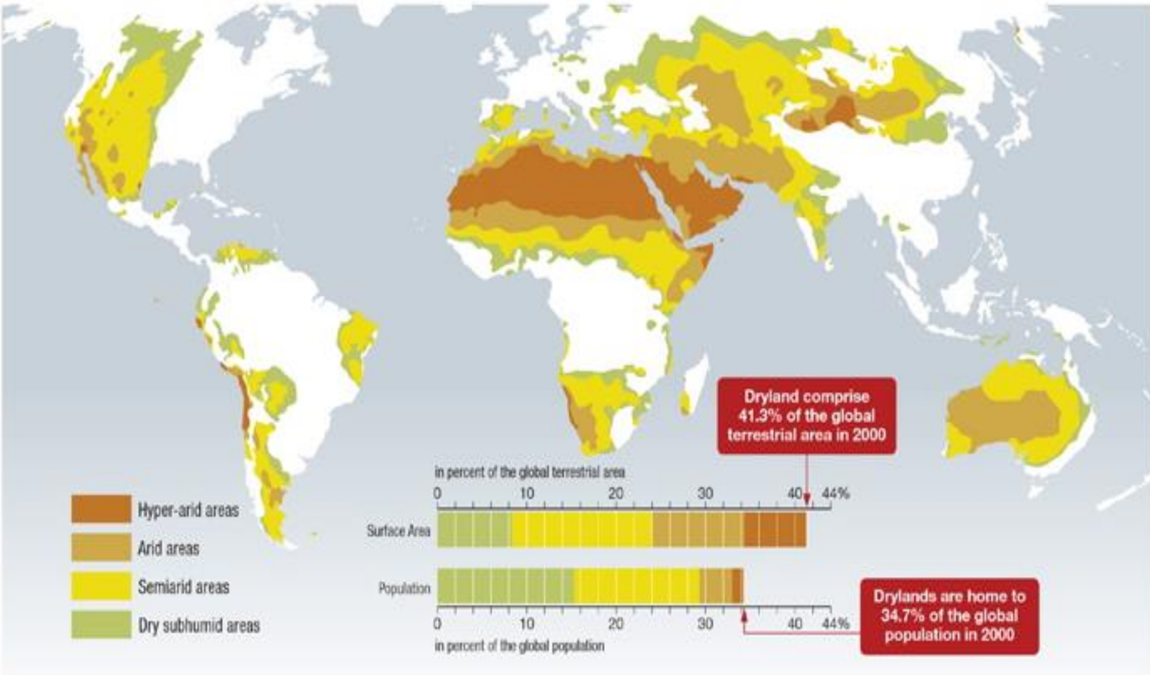

Figure 2. Different types of drylands vulnerable to desertification (Millennium Ecosystem Assessment).

If deprived of vegetation and water, the unprotected soil surface may suffer sediment loss at the hand of wind-driven forces (BÄRRING et al., 2003, LU, 1999).

Aeolian processes is the name given to the erosion, transport and deposition of soil particles by wind (KOK et al., 2012, PYE et al., 1990). These mineral particles from weathered rocks are distinguished in terms of their size: in geological sciences, sand refers to particles with diameters between 2000 µm and 62.5 µm (depending on classification scheme), while dust particles (silt and clay fraction) have a diameter below 62.5 µm; in atmospheric sciences, dust is considered easily suspended sediment while sand is less prone to be suspended, forming bedforms instead (e.g. sand dunes and ripples) (KOK et al., 2012, PYE et al., 1990). These smaller particles are part of the atmospheric particulate matter (PM) and, depending on their size, receive different designations. Particles with a mass median diameter of less than 10 µm and 2.5 µm (PM_{10} and $PM_{2.5}$, respectively) attract much attention since these can be inhaled by humans, potentially causing serious cardiopulmonary diseases (VAN EEDEN et al., 2001). Dust particles are able to travel thousands of kilometers from their origin influencing, for example, the planet's climate, air quality, ecosystems, biogeochemical cycles, which means a local or regional problem may present itself with global consequences (BONASONI et al., 2004, JICKELLS et al., 2005, MILLER et al., 1998).

The aeolian processes are divided in different categories depending if they are associated with erosion, transport or sedimentation. Erosion may exist as a) deflation, when wind drag acts directly on loose particles, suspending them, and b) abrasion, where wind-entrained particles promote soil breakdown to an erodible size or impact the surface inducing more sediment to be entrained (PYE et al., 1990, ZOBECK, 1991). The transport of the eroded sediment (see Figure 3) receives different designation depending if the focus is on individual grains or bedforms.

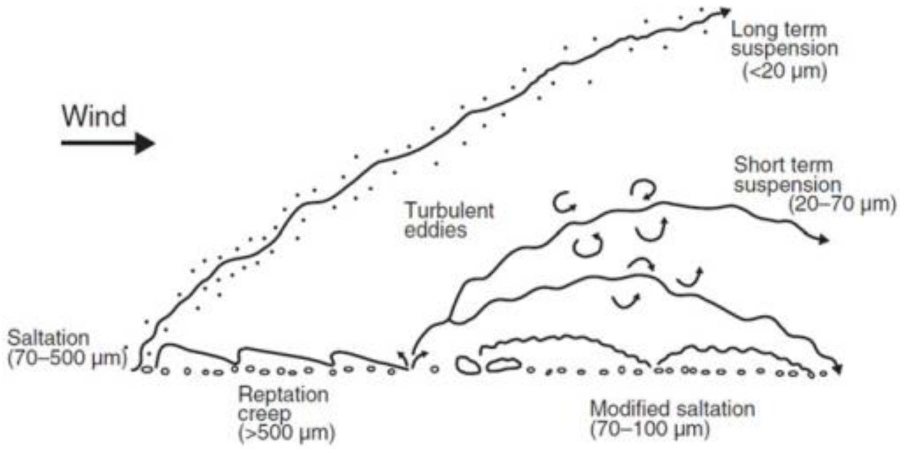

Figure 3. Representation of the different modes of aeolian transport and their relationship with particle size (NICKLING et al., 2009).

Single grains move by saltation, suspension and creep, with the wind velocity and particle size being the determinant factors on transport type (BAGNOLD, 1941, KOK et al., 2012). Dust-sized particles tend to form aggregates by bonding with other particles and do not exist in the soil in free state (ALFARO et al., 1997). While for dust particles, their interparticle cohesive forces overcome the aerodynamic forces, when it comes to larger particles, their movement exists as a consequence of aerodynamic forces. When it comes to bedforms, a clear distinction between transport and depositional processes cannot be made since sedimentation may occur simultaneously with bed form migration (PYE et al., 1990).

1.3.2. Factors influencing wind erosion

The complex interacting processes whereby wind erosion may exist are related to a wide range of factors that can be grouped in three categories: (1) weather and climate (majorly high winds); (2) soil state (particle size characteristics, crusting and aggregation, and soil moisture) and (3) surface roughness (nonerodible aggregates and vegetation cover). Land management practices may also influence the erosion processes (SHAO et al., 1997).

The Earth’s surface interacts with the wind by inducing a drag which reduces the wind velocity close to the surface. The bottom 10-15% of the boundary layer that is developed above the surface is characteristic of the roughness itself (KJELGAARD et al., 2004). In the presence of intense wind events the boundary layer presents a neutral stability condition and wind velocity vertical profile is described by a well-know semilogarithmic equation of the form:

$$u(z) = \left(\frac{u^*}{k}\right) * ln\left(\frac{z}{z_0}\right) \qquad \text{Equation 1}$$

where *u(z)* is the wind speed at height *z*, *u** is the friction (or shear) velocity, *k* is the von Kármán constant (0.4), and z_0 is the aerodynamic roughness height (ZOBECK & VAN PELT, 2014). Both the friction velocity and roughness height are parameters extremely useful in scaling and modeling wind erosion and dust emission events, and in determining the near-surface transport processes (IVERSEN et al., 1994, KJELGAARD et al., 2004). The friction velocity is related to the shear stress developed on the surface by wind and the atmospheric turbulence, while the roughness height is the theoretical height where wind velocity is considered zero (ZOBECK & VAN PELT, 2014). The latter depends on the surface characteristics since it represents also the capacity of the surface to absorb momentum. The threshold friction velocity (TFV) designates the velocity corresponding to the moment for the initiation of particle movement. Although the energy present in the wind movement is responsible for erosion taking place, it is the condition of the soil surface that will define if erosion occurs and, if so, to what extent (ZOBECK & VAN PELT, 2014).

Soil properties influenciate wind erosion and texture is one of the main soil characteristics that may indicate if soil is susceptible to wind erosion. Soil texture is divided in different classes (see Figure 4) based on specific proportions of sand, silt, and clay which help distinguish one type of soil from another.

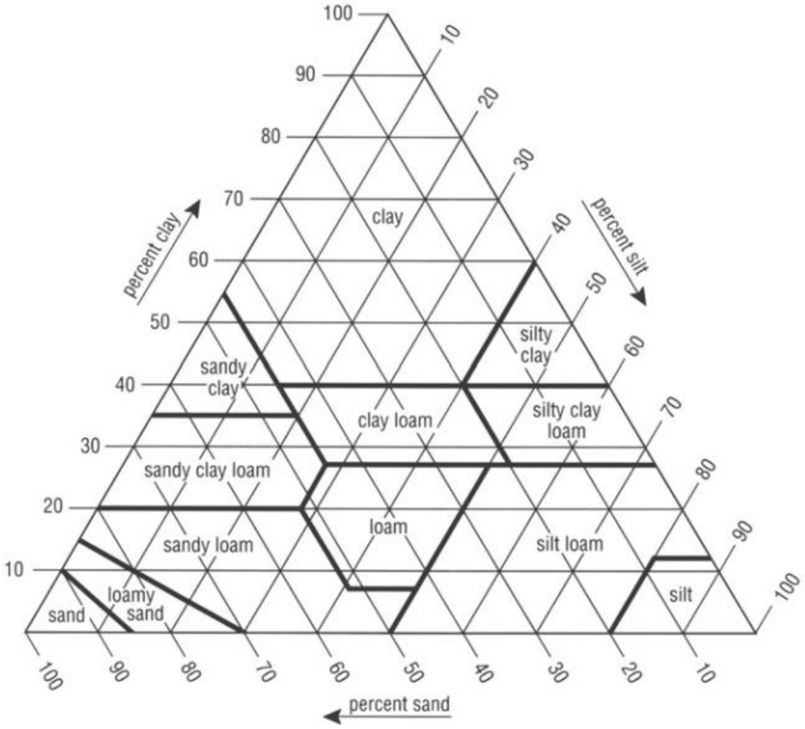

Figure 4. Soil textural triangle (adapted from ZOBECK & VAN PELT. (2014)).

Sands are coarser soils that are more erodible than finer-textured soils such as the clay loam type, while calcareous soils are more susceptible to suffer erosion then noncalcareous soils (ZOBECK & VAN PELT, 2014). Although these are inherent characteristics that take a long time to present any change, there are reports of soil surfaces coarser-textured when compared to a few decades before. This may happen due to a long period of time under the influence of erosive forces and will eventually reduce the soil fertility (LYLES, 1975, ZOBECK & VAN PELT, 2014).

Crusts which are relatively thin and consolidated surface layers above the actual soil surface may eventually appear, being more compact and cohesive than the material immediately below. In these cases, particles are bound together which makes them less susceptible to abrasion by airborne sediment. A great variety of physical, chemical and biological processes may contribute to the crusts formation (ZOBECK & VAN PELT, 2014). Biological soil crusts, for example, help the process of formation, stability and fertility of soil, preventing soil erosion by wind and water, and enabling vascular plant colonization as well as helping with sand dune stabilization (ZHANG et al., 2006).

In a specific area, characteristics as the erosivity of wind, soil type, topography and agricultural practices are usually relatively constant (CHEN et al., 1996). Contrary to these, soil moisture is one characteristic which may present considerable changes throughout different time scales and can, therefore, influence greatly the erodibility of soil by wind. Electrostatic forces, van der Waals forces and forces caused by interstitial water are the bonding forces present in soil (FUNK et al., 2008). Interstitial water is responsible for the formation of liquid-bridge bonding (capillary forces) or adsorbed-layer bonding (adhesion forces). Electrostatic forces, which are weaker than the others, are usually omitted in most studies (CORNELIS et al., 2004). Currently, much of the scientific research was done in laboratory wind tunnels and adress the effect of different moisture content in the critical threshold, simulating the entrainment process with a wide range of wind velocities and soils (CHEN et al., 1996, CHEPIL, 1956, WANG et al., 2014, WIGGS et al., 2004). In the majority of the studies, the increase of water content in soils is related with the reduction of wind erosion and dust emission. In addition, air humidity and adhesives forces between fine particles have also been proven to affect soil erodibility (FUNK et al., 2008, RAVI et al., 2004).

The presence of vegetation has a positive effect on the soil, reducing soil loss by wind in three ways: (1) covering the surface and sheltering the soil from the erosive force of the wind, (2) reducing the wind velocity by removing momentum from the flow and (3) trapping entrained particles, acting as a catchment for sediment deposition (WOLFE et al., 1993). The presence of nonerodible elements (elements too large to be moved by lifting forces) reduces erosion processes eficiency by absorving part of the global stress exerted on the soil, which reduces the stress on the intervening surface where erodible particles can be found (ALFARO & GOMES, 1995).

1.3.3. Wind erosion prediction and control

A number of principles are mentioned as ways of controlling wind erosion, them being: stabilizing sediment with various materials, producing a rough and cloddy surface, using barriers for reducing effective field width and establishing and conserving sufficient vegetative cover (SKIDMORE, 1986, WOODRUFF et al., 1977).

WOODRUFF et al. (1965) established a relationship where all these principles were included and developed the Wind Erosion Equation (WEQ) in the form *E = f(I, K, C, L, V)*, where *E* is potential average annual soil loss per unit area, *I* is a soil erodibility index based on fraction of nonerodible soil aggregates (particles > 0.84 mm) in the erodible size range, *K* is the soil ridge roughness factor, *C* is a climatic factor, *L* is the unsheltered median travel distance of wind across a field and *V* is a equivalent quantity of vegetative cover. The development of this equation made possible to assess the potential erosion from a field and the field conditions (soil clodiness, roughness, vegetative cover, sheltering by barrier, width and orientation of field) necessary to reduce the potential to a tolerable level (SKIDMORE, 1986). However, there was still a need of including management factors with impacts on soil erosion and this problem led to the development of the Wind Erosion Prediction System (WEPS) and the Revised Wind Erosion Equation (RWEQ) (FRYREAR et al., 1999).

The WEPS model was developed by the United States Department of Agriculture Agricultural Research Service (USDA-ARS) which allowed the conversion of WEQ (annual time) to a daily time step model and includes outside influences on surface susceptibility to wind erosion (e.g., crop growth, climate, tillage, etc) (LYLES AND TATARKO, 1986) and conservation of mass and momentum principles applied to wind erosion processes (COLE, 1985), amongst other information. RWEQ combines empirical and process modelling where wind is considered the basic driving force since, regardless of the soil type, it is the wind transport capacity that defines the extent of the erosion event. While the output of WEQ is the average soil erosion in a given field, in RWEQ it is the transport mass, meaning the “mass of soil being transported by wind in a band of unit width that extends from the soil surface to a specific height of 2 meters” (FRYREAR et al., 1999).

The best way to prevent erosion from happening is to limit the contact of wind with the soil surface which is achievable if an effective cover of residue, such as cover crop, is maintained (COPELAND et al., 2009). No-till and conservation tillage practices have been proved to be successful for a more effective post-harvest standing and flat residue over cropped ground. Tillage is also applicable in bare soils or soils with limited crop residues where raising beds perpendicular to the prevailing wind direction and addition of non erodible aggregates may increase the aerodynamic roughness and minimize the ocurrence of sediment transport by saltation (ZOBECK & VAN PELT, 2014).

The use of barriers or fences in fragile soils with low dry aggregate stability, where erosion may start from localized areas before spreading to the entire field, can establish the condition for deposition to occur and discourage saltation (CORNELIS & GABRIELS, 2005). In regions characterized by intense rainfall and where the soil has low wet aggregate stability, the smoothening of the crusted surface along with the presence of loose sand sized material are good conditions for erosion to exist. To prevent this, instruments used for crust breaking and clod forming tillage (rotary hoe or sand fighter) help create random roughness to the field surface (ZOBECK & VAN PELT, 2014).

1.3.4. Wind tunnels and soil erosion

Wind erosion may be studied directly in the field (GILLETTE, 2004, KJELGAARD et al., 2004, ROTNICKA, 2013) where weather and surface conditions are impossible to control, which may present challenges to the implementation of the experimental work. When this is the case, the use of wind tunnels to study the aeolian processes is one possible solution. Wind tunnel testing may be done in close and controlled facilities, thus allowing the study of each variable separatelly in undisturbed environments where conditions are maintained constant long enough to perform the experiments (GENIS et al., 2013, LU, 1999, PYE et al., 1990, RICE et al., 2001). These instalations receive the designation of laboratory wind tunnels. Wind tunnels may also be applied to the field, for in-situ testing and because of this receive the designation of portable field wind tunnels (MACPHERSON et al., 2008, VAN PELT et al., 2013, SHARRATT et al., 2010, ZOBECK et al., 2013). Possible disadvantages of wind tunnel testing are mostly related to problems on the scale application but normally challenges are overcomed if proper care is taken (PYE et al., 1990).

Laboratory wind tunnels are usually from one of two types: closed-circuit or open-circuit wind tunnels. For the first type, the principal characteristic is easily noticed since, by being closed, it has continuous air flow circulation. As for open-circuit wind tunnels, these have a straight line design and are typically composed of three main elements: entrance cone, test section and diffuser. Air is drawn by the fan into the test area after passing a bell-shaped entrance section (NICKLING et al., 1997). The air, then, passes the diffuser before being blown out by the fan (ALFARO & GOMES, 1995). The fan may also be presented in the beginning of the tunnel if it is a blowing-type one (ZHANG et al., 2006) but, for this arrangement, problems related to the airflow are more likely to exist (BAGNOLD, 1941). Closed-circuit wind tunnels are more expensive and harder to build but achieve higher efficiencies while open-circuit tunnels have a low cost simple design, but need to be housed inside a building because are sensible to outside winds (MAYYA, 2012, PYE et al., 1990).

Open-floored wind tunnels applied on the field may be used instead, once these can overcome limitations encountered in laboratory ones, “especially in the assessment of natural soil surfaces for erodibility and dust emissions” (VAN PELT et al., 2010). Field wind tunnels started being used on research after the 1950s and since that time have helped scientists with soil erodibility measurements, influence of surface and cover characteristics on erodibility and dust emissions from eroding surfaces (PIETERSMA et al., 1996, VAN PELT et al., 2010, ZINGG, 1951).

The majority of the study on aeolian processes in wind tunnels has been focused in three main topics (PYE et al., 1990), them being, (1) the threshold for the initiation of particle movement (GREELEY et al., 1980, IVERSEN et al., 1982, SELAH et al., 1995), (2) particle trajectories (DONG et al., 2004, WELLS et al., 1983) and (3) the particle-bed interaction (NALPANIS et al., 1993). Also highly discussed by the scientific community are wind flow influence over dunes and sediment deposition (GOSSENS et al., 1990, WALKER et al., 2003, WIGGS et al., 1996). Other specific studies as electrostatic interactions of particles and electrical fields generated by wind driven soil particles; abrasion effects of wind-driven sand on building materials, crop plants and biological crusted surfaces; complex and vegetated surfaces; and dust emission rates have also used wind tunnels (KIM et al., 2000, MCKENNA NEUMAN & MAXWELL, 1999, RONEY & WHITE, 2006, VAN PELT et al., 2010, ZHENG et al., 2003).

1.4. Research aim and objectives

The application of biochar to soils has been suggested as a possible way of combating environmental and agronomic challenges such as climate change, soil degradation or reduced crop yield. However, there are still many knowledge-gaps that prevent large-scale field application, one being the possible increase in soil erosion by wind with the application of biochar as a soil amendment. The aim of the present study was to address this knowledge gap by investigating the wind erosion potential of biochar amended-soil with a focus on the effect of soil moisture content, using a laboratory wind tunnel. To achieve this aim, the following objectives were identified:

I. To evaluate the wind tunnel conditions for wind erosion studies;

II. To develop a wind tunnel methodology for investigating soil erosion by wind;

III. To use the developed methodology to study wind erosion of bare soil and biochar-amended soil at a range of moisture contents.

1.5. Relevance and applicability of results

Having the research aim in mind, the results obtained in this pilot study are therefore expected to fill in a gap in the current scientific knowledge on the wind erosion potential of biochar-amended soils and may serve as a basis for future studies on this matter. The results originated by this study are expected to enrich the body of scientific evidence on the interactions between biochar application and soil erosion, considered as threat to soil, as identified by the Thematic Strategy for Soil Protection (COM(2006) 231). The importance of this work lies on the need to deeply understand the interactions between biochar and soil properties and processes because, only then, effective legislation can be developed for the use of biochar on soil.

1.6. Organization of the dissertation

Chapter 1 - GENERAL INTRODUCTION, RESEARCH AIMS AND RELEVANCE

Soil erosion by wind	*Biochar*	*Hypothesis*
Definitions Inducing agents Methods for assessing wind erosion	Introduction of the concept Material characterization Interactions with soils	Biochar particles erode at lower wind velocities than mineral particles Amended soil has different threshold moisture content than the control soil Biochar increases dust production in an erosion event DAO wind tunnel is adequate for wind erosion studies

Chapter 2 - SOIL EROSION IN WIND TUNNELS

Methodology Development

Description of the wind tunnel facility and equipment used in the experimental work
Preliminary study (previous investigation, pilot tests implemented) that led to the definition of the chosen methodology
Definition of the methodology

Chapter 3 - EROSION OF BIOCHAR-AMENDED SOIL IN WIND TUNNEL

Methodology Application

Properties of biochar and soil used in the experimental work
Explanation of the procedures for sample preparation and experimental runs
Presentation and analysis of the results obtained with the application of the methodology

Chapter 4 - CONCLUDING REMARKS

Final conclusions of the research carried out and its contribution for future studies with relevance on the applicability of the methodology and outcomes from the tested hypothesis

II SOIL EROSION IN WIND TUNNELS – METHODOLOGY DEFINITION

2.1. Introduction

The simplest simulation of a wind erosion system in wind tunnels is obtained by having loose dry sand particles with uniform size and density entering saltation or creep movement and, for this case, there is much progress on understanding the physics behind it and modelling its behaviour (ANDERSON et al., 1991, HAGEN, 1999). However, when variables as surface moisture, bed shape, non erodible elements or grain size are included, understanding erosion processes becomes a hard task and more research is still needed (HAGEN, 1999). For agricultural soils, difficulty is even greater because systems include the “presence of a wide range of aggregate sizes, abrasion of immobile clods/crusts, breakage of the moving saltation/creep to suspension size, trapping of moving soil by vegetation or microrelief, and vegetation effects on airflow” (HAGEN, 1999).

ALFARO et al. (1997) and DONG et al. (2004) added sand to the wind tunnel test section and determined horizontal sand fluxes by collecting the saltating particles in vertical sand traps (modified Bagnold and vertical chambered type, respectively; see Figure 5) and weighing the sediment. In the first study, vertical fluxes were also determined by replacing the sand trap by an horizontal rectangular opening in the tunnel floor. While here, sand was spread along the wind tunnel section, for the other case, a tray with sand was placed in the test section, leveled with the floor and large enough for saltation to exist (400 x 80 x 2.5 cm). Additionally to the horizontal sand flux DONG et al. (2004) also applied double-sided sticking tape to the tunnel floor downwind of the tray which captured moving grains by adhesion. The wind was considered to reach the particle initiation threshold when more than five particles were stuck on the sticky tape, and this allowed determination of the TFV. ALFARO et al. (1997), in a second experiment, substituted the traps by a floor-leveled tray full of clay, upwind of a particle collecter containing a filter holder, to investigate dust production by saltation, as in SHAO et al. (1993). However the latter used a vertically integrating trap (modified Bagnold type, see figure 5) instead, but in both methods the air was drawn through the equipments to improve sampling efficiency.

Contrary to wind tunnel saltation studies, there is not much progress oriented to the velocity of saltating particles in the literature, according to YANG et al. (2007). Optical sensors have been used to capture sand particles velocity fields in the wind flow by detecting differential light effects caused by grains crossing a laser sheet (BUTTERFIELD, 1999). An example of this method, Particle Image Velocimetry (PIV), was used by YANG et al. (2007) to study the height profile of the mean velocity of an aeolian saltating cloud. In addition to an optical method, BUTTERFIELD (1999) also employed a passive chambered sand trap (Aarhus type) to determine mass fluxes.

CORNELIS et al. (2003), CORNELIS et al. (2004), HAN et al. (2009) and VAN DIJK et al. (1996) investigated the effects of moisture on sand transport. With exception to HAN et al. (2009) in all studies moistened coastal sand left a tray levelled with the test section and entered a saltiphone that detects windblown particles larger than 50 µm through an acoustic system (microphone), allowing the determination of the saltation threshold (SPAAN et al., 1991). VAN DIJK et al. (1996) also measured the sediment lost by weighing the tray, before and after runs in oven-dried conditions, and used a sand trap (De Ploey vertical sand trap) to obtain the particles mass distribution with height. In the same way, HAN et al. (2009) weighed the sand trays before and after the experiments but applied a similar procedure as DONG et al. (2004) with sticking tape on the tunnel floor to determine the TFV.

The addition of non-erodible roughness elements also increases the complexity of the wind erosion systems. MCKENNA NEUMAN (1998) incorporated an external sediment delivery equipment to promote saltation over a sand bed placed on top of crushed gravel and beach shingle. A VHS camera on top of the tunnel recorded changes to the surface (for subsequent digital treatment) while a wedge-shaped trap collected the saltating particles for mass flux determination. In MUSICK et al. (1996) roughness elements representative of vegetation stuctures were affixed to a base plate. Initiation of sediment transport was observed with the sticking tape method described above and a Sensit^{TM}, which has a sensor that allows the detection of saltating particles.

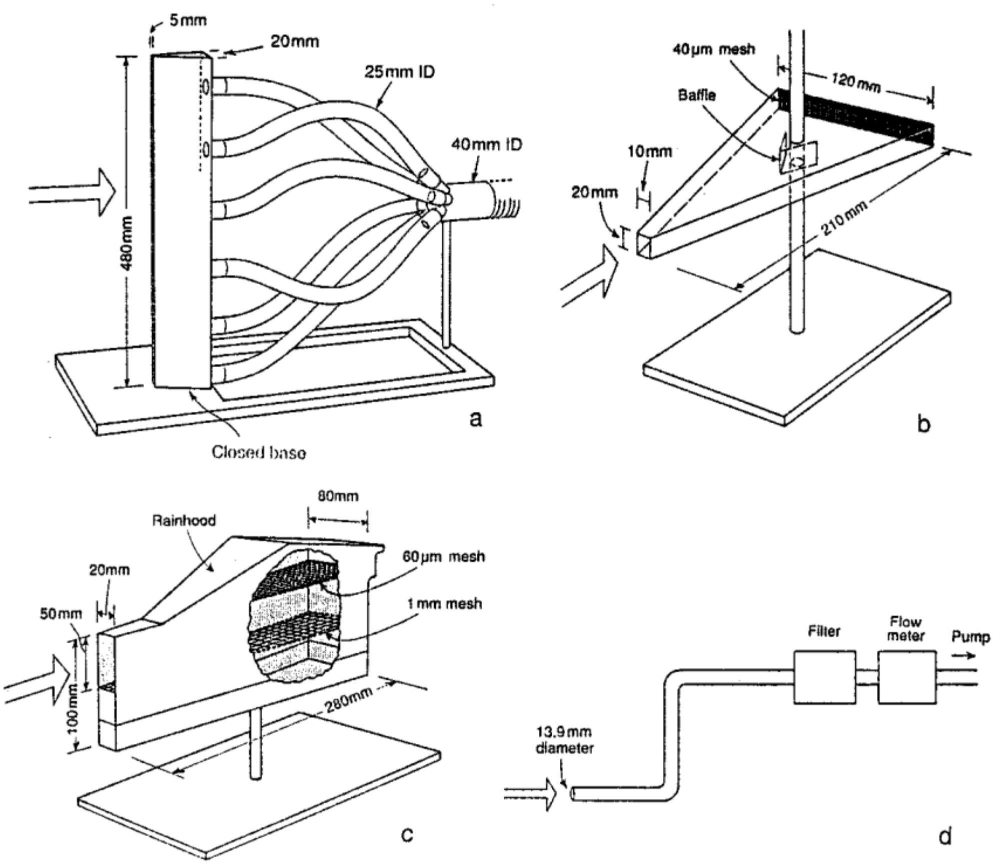

Figure 5. Examples of sediment collectors used in wind erosion studies: (a) Vertically integrating (modified Bagnold) trap. (b) Leach trap. (c) Fryrear trap. (d) Isokinetic sampler (adapted from SHAO et al. (1993)).

Compared with uncultivated soil, cultivated soil undergoes more serious wind erosion. Soil surface roughness created by tillage, for example, is an important feature that significantly affects wind erosion on cultivated soils. ZHANG et al. (2004) tested the aerodynamic roughness of a cultivated soil from a farmland by the determination of the wind profile above the soil surface with a vertical stack of Pitot tubes. The author also used a step-like silt passive sampler for collecting the eroded soil in order to determine a relationship between aerodynamic roughness and soil wind erosion. SHARRATT et al. (2010) examined possible alternatives to conventional tillage for minimizing the emission of windblown PM_{10}. For that, the author used a slot sampler (modified Bagnold type) for coarser particles and an optical analyzer (DustTrak aerosol monitor) to determine the dust fraction concentration. ZOBECK et al. (2013) studied the soil properties (organic matter content, aggregate density, stability, and erodible fraction) effects on wind erosion of organic soils with an aspirated soil sampler and an optical particle size analyzer to determine the PM_{10} and $PM_{2.5}$ levels.

The objective for the study described in the following chapter is to test the DAO wind tunnel conditions for wind erosion studies and select a robust method to collect sediment emitted from wind erosion of soil, from the coarser particles to the dust fraction.

2.2. Methods and materials

2.2.1. The wind tunnel of the Department of Environment and Planning

Wind tunnel description

The wind tunnel used to perform the experiments is located at the Department of Environment and Planning at the University of Aveiro, Portugal. The schematic in Figure 6 describes the wind tunnel as an open-circuit sucking-type wind tunnel with a test section of 7 x 1.5 x 1 meters (L x W x H).

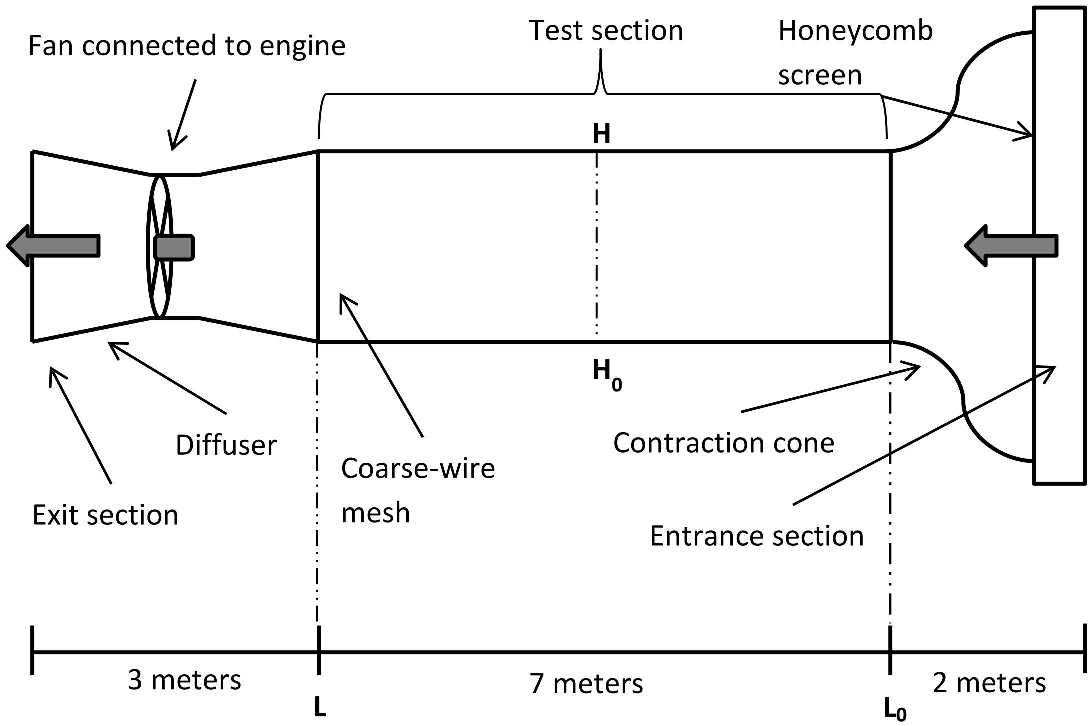

Figure 6. Schematic representation of the elements that compose the DAO wind tunnel before the methodology definition.

The air enters the wind tunnel at the intake passing through a flow-straightening section directly to a contraction cone. The honeycomb screen reduces the free stream turbulence level (ALFARO & GOMES, 1995) and the contraction cone increases the velocity of the air flow towards the test section (COPELAND et al., 2009). After the test section there is a coarse-wire mesh and a conical diffuser leading to an engine which is connected to a fan. The diffuser smoothly reduces the air flow velocity without creating turbulence in the test section (ZELL, 1993).

Boundary layer development

The wind tunnel size or characteristics may differ depending on the type of study to be implemented (ALFARO & GOMES, 1995, BUTTERFIELD, 1999). The size of the test section, for example, can vary from those large enough to fit a commercial aircraft to the ones larger than a few square centimeters (FINGERSH et al., 2001, PORNSIN-SIRIRAK et al., 2001, WRIGHT et al., 1955). When it comes to the simulation of the atmospheric boundary layer, even in wind tunnels with test sections up to 20 or 30 meters in length, it is still necessary to have additional elements helping the layer's development. In larger test sections a small barrier followed by a rough surface such as gravel or sandpaper is enough while, for the small ones, vortex generating elements are needed (BUTTERFIELD, 1999, CORNELIS et al., 2003, CORNELIS et al., 2004, CREYSSELS et al., 2009, LEYS et al., 1998). In the present study a setup of turbulence generators and roughness arrays (see Figure 7 and 8) were placed in the first meters of the test section, as it is shown in Figure 7.

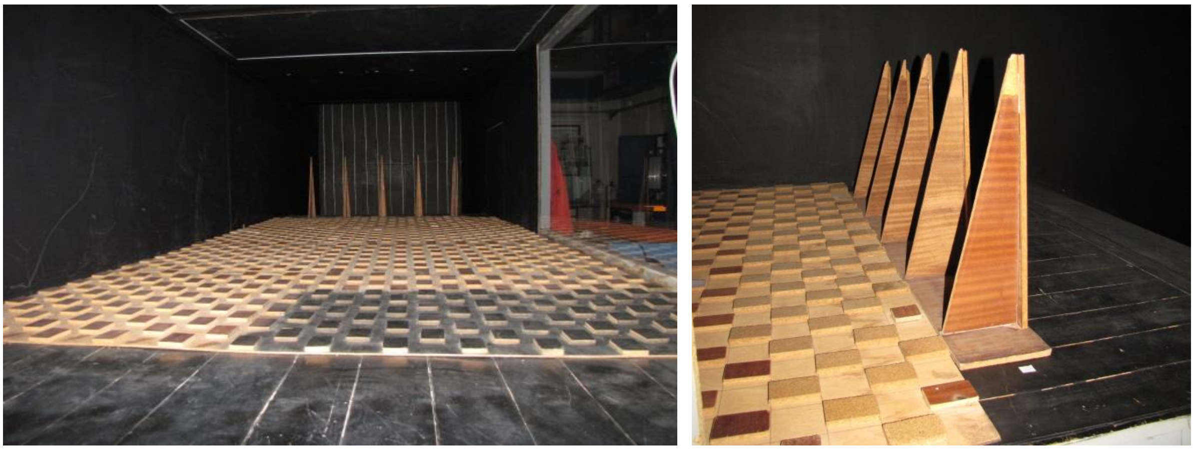

Figure 7. Setup of turbulence generators and roughness arrays located in the beginning of the wind tunnel test section.

The elements consist in a group of five spires that reach the height of 45 cm and, right after, four wooden boards, each with the length of 75 cm. Small blocks are attached to the boards forming the array that extends throughout the tunnel width and reaches the length of 3 meters. The characterization of the elements is shown in Figure 7 and 8.

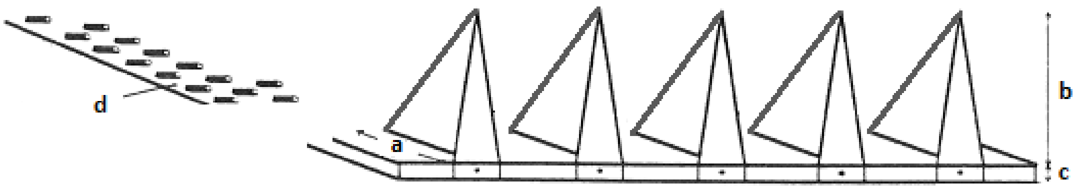

Figure 8. Characterization of the turbulence spires and roughness array (wooden board), adapted from COSTA et al. (1994). The roughness array blocks (d) are 6 x 4 x 1 cm (L x W x H). As for the spires, a, b and c represent 15, 43 and 2 cm, respectively.

The use of turbulence spires combined with the floor roughness transforms the uniform flow upwind of these elements into turbulent flow consistent with the conditions in the natural surface of the planet (see figure 9) (IRWIN, 1981).

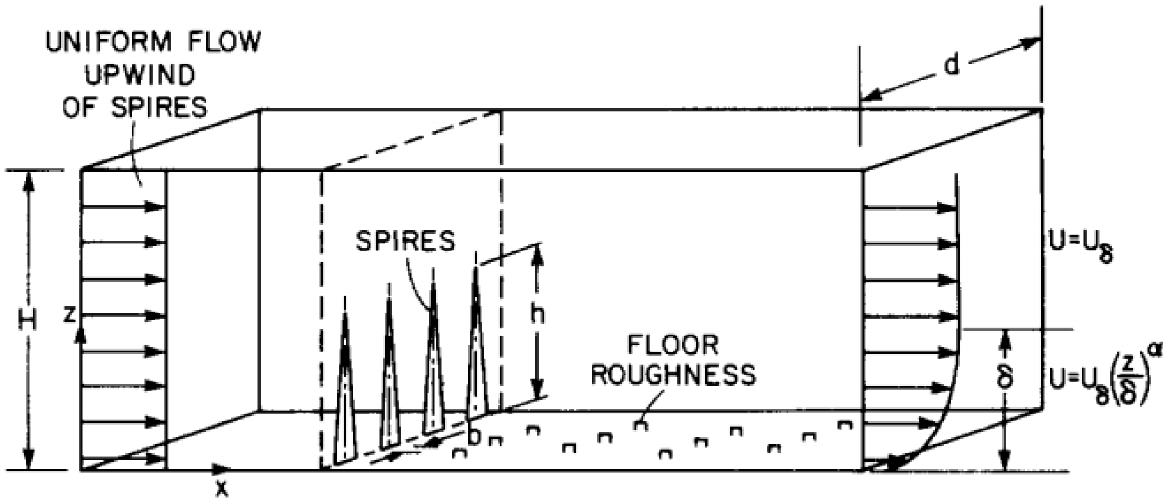

Figure 9. Spires and floor roughness inside a rectangular test section and representations for the vertical profiles of wind velocity across the boundary layer (adapted from IRWIN (1981)).

The wind flow inside the tunnel is generated by an AC motor connected to a large fan and a variable frequency drive. The velocity was measured with a Pitot tube connected to a manometer that gives the difference between the total pressure and the static pressure of the flow. This pressure loss represents the contribution of velocity (through the dynamic pressure) to the total pressure. The measured pressure difference is converted to velocity using Equation 2, from the application of Bernoulli's equation.

$$U = \sqrt{\frac{2 \times \Delta P}{\rho}} \qquad \text{Equation 2}$$

In equation 2, U is the wind flow velocity, in m s^{-1}, ΔP is the pressure difference, in Pa, and ρ is the air density, in $kg\ m^{-3}$, at the room temperature.

2.2.2. Sediment loss by tray weighing

The application of trays to accommodate the sample, as shown on other erosion experiments in wind tunnels (see Table 2), could be a viable approach to this study. In the literature, there was not a standard type of tray used by the authors.

Table 2. Tray dimensions and surface area identified in methodologies observed in the literature and comparison with the trays available for the present study.

Surface area	Tray size [cm]			Method
	Length	Width	Height	
[m^2]	[cm]			
0.10	31	31	4	GENIS et al. (2013)
0.12	50	24	5	HE et al. (2008)
0.15	50	30	15	ZHANG et al. (2004)
0.20	100	20	1.5	SHARRATT et al. (2013)
0.21	56	37	2	HAN et al. (2009)
0.30	100	30	25	CHEN et al. (1996)
0.38	95	40	2	CORNELIS et al. (2003)
0.38	95	40	2	CORNELIS et al. (2004)
0.40	120	33	3	DE VOS (1996)
0.40	80	50	9.7	WANG et al. (2014)
0.45	150	30	1.5	ARGAMAN et al. (2006)
0.46	100	46	1.5	RAVI et al. (2006)
0.50	100	50	4	COPELAND et al. (2009)
0.70	200	35	2.7	CAMPBELL et al. (2002)
0.78	120	65	1.5	ARGAMAN et al. (2006)
2.00	250	80	2	YANG et al. (2007)
3.20	400	80	2.5	DONG et al. (2003)
0.08	29	28	4	
0.20	70	29	3.4	Present study
0.28	100	28	3.4	

A plastic tray with the dimensions 29 x 28 x 4 cm (L x W x H) containing only soil (previously air-dried and sieved over 2 mm) was laid down in the center of the test section width, at a distance of 150 cm from the coarse-wire mesh. The soil full characterization will be presented later in Section 3. Due to its size, this tray could be placed on top of an electronic balance available (± 0.01 g precision) and the weight measured. Wind tunnel runs of 20 minutes were performed using different free stream velocities (2, 4, 6, and 8 m s^{-1}) that generated wind speed with magnitude distinguished by naked eye (CAMPBELL et al., 2002). The run duration was considered to have enough time for performing this type of test, according to other wind tunnel studies (BUTTERFIELD, 1999, HE et al., 2008). The plastic tray was weighed before and after the runs with the purpose of trying to quantify the sediment lost for each velocity (CHEN et al., 1996, HAGEN, 1991, HAN et al., 2009).

In studies similar to this (shown in Table 2) the tray was levelled with the test section floor but, in this case, there was no availability on any type of system that could adjust the tray height. Aiming to identify, by the use of a visualization technique, possible disturbances on the flow induced by the tray borders, a laser device was placed through a hole in the tunnel ceiling oriented to focus on the tray. With the use of a smoke-generator, the laser beam focus on the smoke particles producing a laser sheet parallel to the wind flow (BORREGO et al., 2007). This setup allowed the visualization of possible disturbances on the flow induced by the surface roughness and the tray borders. The smoke machine was positioned outside the wind tunnel near the tunnel inlet and smoke was forced to enter the test section. The amount of smoke produced was adjusted with a control connected to the machine. A slow wind velocity was chosen because the turbulence created by higher velocities could make the flow visualization impossible. The wind tunnel interior is black-coloured to minimize the possibility of the laser causing damage to the eyes due to the reflection of the laser beam. During the visualization, all the laboratory windows were covered so that the natural light would not interfere with the experiment.

The observation described above was replicated with different experimental conditions. Not only the plastic tray was used but also a larger metal tray with the dimensions of 100 x 28 x 3.4 cm (L x W x H). This was the largest tray available but smaller than the ones where a significant saltation cloud could be promoted (DONG et al., 2003, YANG et al., 2007). Runs with different wind flow velocities (between 1 and 6 m s^{-1}) were tested to obtain the best visualization. A digital video camera (supported in a tripod) outside the tunnel was focused on the tray surface and recorded the experiment for further analysis.

2.2.3. Initiation of particle movement, sediment collecting area and transport distance

DONG et al. (2003) and HAN et al. (2009) applied sticking tape on the wind tunnel test section floor to determine the moment when sediment entered the saltation mode. ZHANG et al. (2012) did not apply the tape but used a high definition digital camera to record movement initiation. Following these methods, a set of runs on the particle movement by visual observation was also carried out in this experimental work. Behind this study was the need to gather information on the wind velocity range to be chosen for the following wind erosion simulations, given the wide variety of velocities seen in the literature (see Table 3). In the first tests, a metal tray (described above) full of soil (previously air-dried and sieved over 2 mm) was put in the middle of the test section width, distancing 65 cm upwind the coarse-wire mesh and 2.5 meters downwind from the roughness arrays. The wind flow velocity was first slowly and continuously increased (1 m s^{-1} step) until movement of particles in the tray was observed at naked eye (ZHANG et al., 2012) and, then, until the maximum velocity was obtained (15 m s^{-1}). Each velocity was maintained steady during 2 minutes, according to other studies in the literature (CHEN et al., 1996, CORNELIS et al., 2003, CORNELIS et al., 2004). A digital video camera recorded the experiment (as described in 2.2.2.) to help determine the threshold wind speed inducing particle movement.

Table 3. Free stream velocities used in other experiments described in the literature.

Free stream velocity [m s^{-1}]	Method
6	CORNELIS & GABRIELS. (2005)
12	ZOBECK et al. (2013)
14	WANG et al. (2014)
16	SHARRATT et al. (2010)
13, 16	HAGEN (1991)
6, 7 , 8	COPELAND et al. (2009)
6, 10 , 12	ERPUL et al. (1998)
6.5, 11, 18	BUTTERFIELD (1999)
8, 10, 12, 14	YANG et al. (2007)
8.0, 9.5, 11.0 , 12.5	SHAO et al. (1993)
10, 15, 20, 25	ZHANG et al. (2004)
6, 7.2, 8.4, 9.6, 10.8, 12	LEYS et al. (1998)
3, 5, 7, 9, 11, 13	CAMPBELL et al. (2002)

Methods for collecting eroded particles usually include sediment samplers where the mass of sediment deposited is continuously weighed or removed to be weighed once the run is finished (HOUSER et al., 2001b, LEYS et al., 1998, MACPHERSON et al., 2008). In the literature there are also studies with wind tunnels that allow the addition of a collection area downwind of the test section (CREYSSELS et al., 2009, NICKLING et al., 1997, WANG et al., 2014). Although the wind tunnel employed for this study had a considerably smaller test section, an attempt was made to collect sediment downwind of the tray and to have some perception about its transport distance.

In the first experiment, 8 metal collecting trays (2 rows of 4) were put inside the wind tunnel test section, next to the coarse-wire mesh, parallel to the wind flow. Upwind from these, another one was laid down, the same way, in the middle of the section, full of soil (previously air-dried and sieved over 2 mm). Additionally to this setup, the tray was also positioned transversal to the wind flow, in other test. The total length available for sediment collection was close to 1.5 meters. The engine was turned on, starting with a free stream velocity of 6 m s^{-1}. This velocity was increased again directly to 10 m s^{-1} and, finally, to aprox. 13 m s^{-1}. At each step the velocity was maintained constant during 4 minutes (MACPHERSON et al., 2008, VAN PELT et al., 2013, ZHANG et al., 2004). The chosen wind velocities (6, 10 and 13 m s^{-1}) represent minor, medium and major erosion events, respectively (COPELAND et al., 2009, ERPUL et al., 1998, ERPUL et al., 2002, ZHANG et al., 2004).

In a second test, a total number of 17 trays were inserted into the wind tunnel (figure 10). They were disposed as 4 rows of 4, parallel along the test section width, reaching to 2.8 meters, in terms of the length for collected sediment. Contrarily to the first case, the sample tray was only put transversal to the wind flow due to length constraints, since it was already near the roughness elements. The setup did not extend along the total tunnel width but this was not considered as a deterrent factor for the test. Three velocities (6, 10 and 13 m s^{-1}) were tested, but now, in independent runs for 20, 15 and 10 minutes, respectively, which are durations practiced in other research methods (DE VOS, 1996, HOUSER et al., 2001b, ZOBECK et al., 2013).

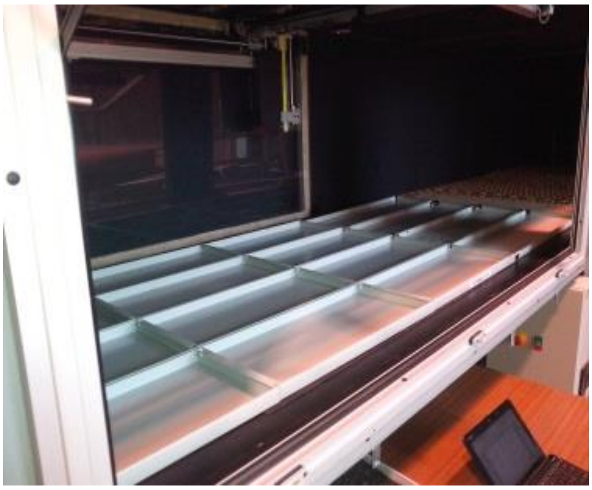

Figure 10. Test section configuration for the second test where 16 collecting tray were used with the sample transversal to the flow.

2.2.4. Sediment dust fraction analysis

Although the experiment described in 2.2.3. could allow the observation of coarser particles, it would not be useful for finer particles, particularly the dust fraction, because their size makes them undetectable to the naked eye. In previous studies, attempts on quantifying this sediment fraction relied on aspirated samplers or optical dust monitors (ALFARO et al., 1997, ALFARO et al., 1998, FUNK et al., 2008, KENNEDY et al., 2002). Since this type of equipment was not available for this study, a different approach was followed.

In a similar way to the experiment described in 2.2.2. a laser device was placed on top of the wind tunnel oriented to cover the metal tray, as described in the previous sections. The wind flow velocity and run duration was controled the same way as in the 4-collecting tray test: slowly and continuosly increased from 0 to 15 m s^{-1} with 4 minute steps. This time, the tray was full of soil mixed with biochar (fully characterized in Section 3) which visually appeared to have more dust particles susceptible to be suspended when compared with only soil. Therefore, the use of the laser sheet could allow the visualization of a biochar dust cloud which, at clean sight, would be difficult to identify. This procedure was also recorded with a digital video camera for further observation.

An attempt on collecting the less coarse particles was made in a way similar to what happens in particle impaction pre-separators (MAY, 1945). By stapling cardboard to acetate paper where a small portion of silicone was spread, it was possible to have one adherent surface like the one in impaction plates. Five small "squares" with a 36 cm^2 area were marked in the acetate paper with a pen and silicone was spread on it. The adherent surfaces were then clipped to the coarse-wire mesh. The difference in weight of the adherent surfaces before and after the test was determined by weighing in an electronic balance (± 0.000003 g precision). A microscopic, optical or digital analysis could also be possible and could give information, for example, on particle size or mineral characterization. Three adherent surfaces at the heights of 25, 50 and 75 cm were placed in the center of the coarse-wire mesh which is located between the test section and the difuser (see Figure 6). Then, two more were clipped at the height of 50 cm, but 20 cm to the left and right of the center. The surfaces positions were chosen this way in order to have a representative area without influencing greatly the wind flow.

Additionally to the adherent surfaces application, another tray setup was put inside the test section. The sample tray full of biochar-amended soil was laid down parallel to the wind flow with two equal trays by each side and a collecting tray immediately after. In a different approach than the previous experimental tests explained throughout this section, the sample tray was divided with a barrier leaving the last 30 cm empty for creeping particles to be deposited. COPELAND et al. (2009) did not make any separation but used an additional tray attached to the downwind edge of the sample tray, while NICKLING et al. (1997) captured creeping and saltating particles with a vertically integrating, passive trap (Guelph-Trent-Wedge trap). The run was performed with a free stream velocity of 6 m s^{-1} and lasted 20 minutes, which are similar conditions to other procedures explained above.

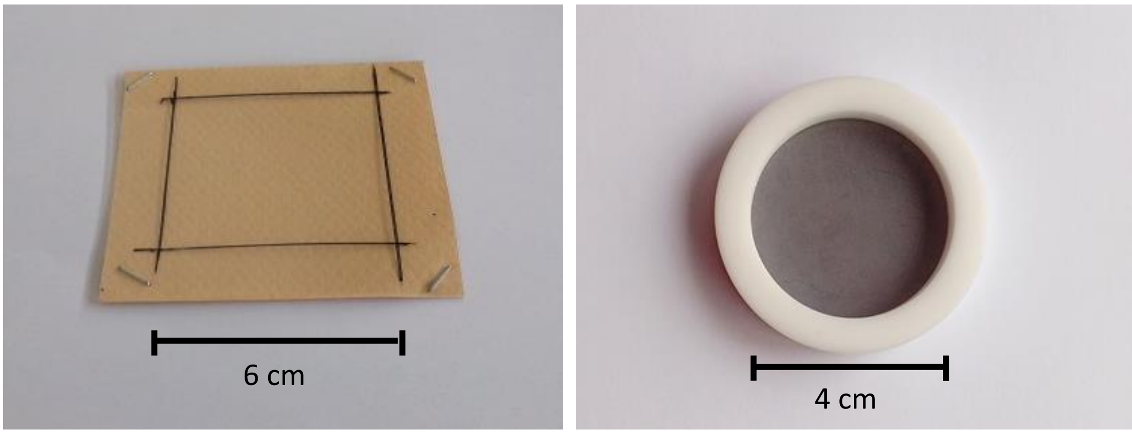

Figure 11. Adhesive surface (left) and filter holder (right).

The same experiment was replicated but now with filter holders (internal diameter of 4 cm) containing glass fibre filters (see Figure 11) (Whatman QM-A quartz fibre filters) used also in air quality monitoring (CASTRO et al., 1999). The filters could permit, besides the gravimetric analysis, an elemental/organic carbon content analysis through thermal optical equipment available in the department (CASTRO et al., 1999).

2.3. Results

2.3.1. Sediment loss by tray weighing

A simple way of having information on the sediment loss throughout an erosion event could be obtained by placing the soil in a tray and measuring the difference in weight before and after that condition. During the wind tunnel runs performed at the two lower free stream velocities (2 and 4 m s^{-1}) there was no visible effective sediment loss. For the higher velocities (6 and 8 m s^{-1}), although some movement was noticed at the soil surface, only a small number of particles left the tray. After each run, the balance showed that there was no difference between the initial weight and the weight measured after the tests.

The fact the tray was not levelled with the floor, contrarily to the studies where this procedure was followed (see Table 2, section 2.2.2.), led to the experiment with the laser sheet and smoke machine. The latter allowed to identify, by the use of a visualization technique, possible disturbances on the flow induced by the tray borders. Initially, a lower velocity was chosen to perform the test since higher velocities increase the wind flow turbulence, difficulting the visualization. With velocity at 1 m s^{-1} the smoke did not circulate, while at 3 m s^{-1} ascended and travelled near the test section roof, hindering any observation. Finally, at 6 m s^{-1} it travelled through the test section, after passing the roughness arrays and spires, and when it reached the tray it was possible to see the disturbance originated by the edge. This barrier made the fluid detach from the tray surface and, consequently, induced the formation of a wake where the air recirculated, forming vortices. This phenomenon was easily visible with both the small plastic tray and the large metal tray, but particularly with this last one.

2.3.2. Initiation of particle movement, sediment collecting area and transport distance

An experiment was done with the purpose of trying to understand the velocity range that should be used for the wind erosion simulations. To evaluate this, the free stream velocity was slowly and continuously increased until movement of particles was observed at naked eye which eventually happened around 5 m s^{-1}. As velocity increased (6 m s^{-1}), particles started leaving the tray and, when wind velocity was close to 9 m s^{-1}, a visible difference in the number of eroded particles was observable. Finally, after 12 m s^{-1}, there was another visible increase which was the last significant change before the end of the experiment.

The unavailability of sampling equipment or collection chambers forced the use of the test section remaining space to collect the deposited sediment that exited the tray. For the 8-trays experiment, movement of particles was observed at 6 m s^{-1}, immediately after the engine being turned on, and a very small number was collected in the trays (mainly on the first row) mostly in the middle. For higher velocities (10 and 13 m s^{-1}) more sediment got collected, while other particles jumped through the entire setup and some of the collected ones, exited the trays. Some particles also rolled along the surface and got lodged below the internal side of the edge, because of the tray shape. The sample tray was located in the center of the test section parallel and transversal to the wind flow but in both cases there was no evident sediment loss through the side of the tray, and subsequent deposition out of the collecting trays.

On the other experiment (16 collecting trays) the observed intensity of the erosion event was different between the three chosen velocities. More sediment was collected in the higher velocity runs (10 and 13 m s^{-1}) but in the last one there were also more particles leaving the collecting trays. One detail common to all experiments is that only the first row downwind of the sample tray had considerable amount of sediment. It was also observable that some particles may be deposited in empty spaces between trays and others may leave the surface and be transported above the entire collecting setup.

2.3.3. Sediment dust fraction analysis

In all the studies seen in the literature, the finer fraction of the eroded sediment was investigated using samplers that aspirate air, filtering the particles, or monitoring the dust concentration directly by the means of optical methods. In the first tests performed, no visible dust cloud was detected by using the laser device, with the camera not presenting useful information, as well. After the end of the experiments, the laboratory floor and wind tunnel interior presented themselves covered with biochar dust, proving the existence of suspended particles in the air flow.

The first problem with the adhesive surfaces appeared with their weight, since it did not stabilize in any of the two most precise balances available (± 3 µg precision). After the test being performed, a small number of particles were attached to the surface but not in enough portion to be quantified. Although no problem occurred with the pre-run weighing of the glass fiber filters, after the experiment they presented themselves blank as in the beginning.

The experiments for collecting the dust fraction were not successful but, on the other hand, there was considerable biochar movement, majorly larger particles, and some mineral particles as well. Almost all sediment got collected in the area for creeping particles while the downwind additional tray did not present any sediment collected. The same happened with the side trays which did not present any considerable sediment when compared with the sample tray collecting area.

2.4. Discussion

The simulation of erosion events in wind tunnels may be obtained by inserting trays with soil in the test section, which are weighed before and after the run being conducted or continously as the run takes place (if mounted in balances inside the tunnel). The change in weight is assumed to be the soil loss through that surface area. Although this was a simple method, when applied in this study, it did not present good results. The smaller wind velocities, 2 and 4 m s^{-1}, only allow transport of the dust fraction (AIMAR et al., 2012, FUNK et al., 2008) and are below the values practiced in similar studies (See table 2, Section 2.2.2.). In CHEN et al. (1996) erosion of a sandy loam soil with a 2.67% MC (and not air-dried as the tested soil) started at 6 m s^{-1}, increased with higher velocities and the maximum run duration (15 minutes) was not greater than in the present experiments. With 7.7 m s^{-1}, 13 g of soil per m^2 of surface area per minute left the tray which indicates that, for the present study, at 8 m s^{-1}, effective erosion should have existed and the tray weight should have decreased. Wind flow difficulty on detaching soil particles could result from tray edge being slightly above the soil surface or the fact that the edge was not levelled with the test section floor as in CHEN et al. (1996) and other studies (see Table 2, Section 2.2.2.). The use of this tray and, therefore, this weighing method was rejected when it was decided to use one of the metal trays for the experiment (which will be explained below), since the metal trays weight surpassed the maximum weight the balance could measure.

Both CHEN et al. (1996) and HAGEN (1991) mounted a balance in the test section in a way to have the tray levelled with the tunnel floor and register sediment loss. This was not an option taking into consideration the time available for the experiments and because changing the wind tunnel structure could bring additional problems to the wind flow conditions on the next studies. The latter could also happen if a collection chamber was added (CAMPBELL et al., 2002, CREYSSELS et al., 2009, NICKLING et al., 1997) and probably there would not be enough space for such modification.

The velocity range to be applied on the experimental tests may depend on different factors, such as the sampling site meteorological conditions or soil characteristics (HE et al., 2008, LU et al., 2013, SHARRATT et al., 2010). In this study, it was observed that the velocities at which particles started moving (5 m s^{-1}) and leaving the metal tray (6 m s^{-1}) are consistent with the other studies in the literature. Usually, 5 m/s is the wind velocity value corresponding to the moment when sand grains start to move (LU et al., 2013). CHEN et al. (1996) and COPELAND et al. (2009) identified the threshold velocity at 6.5 m s^{-1} for sandy and silty soils. ARGAMAN et al. (2006) showed velocities between 6 and 7.5 m s^{-1} for soils with different textures and crusts while BUTTERFIELD (1999) reports 6 m s^{-1} for a sand bed. Other wind velocities, 10 and 13 m s^{-1}, standed out as being suitable for testing, because were associated with a visible increase in the number of eroding particles. Additionally to this factor, they are also mentioned in the range chosen by other authors (see Table 3 Section 2.2.3.) and described as representative of medium and high erosion events, respectively (COPELAND et al., 2009, ERPUL et al., 1998, ERPUL et al., 2002). The experiment to determine the velocity range was performed with the metal tray instead of the plastic one used in the first test. After comparing both tests, it was visible that velocities within the same range presented different results, since more sediment eroded using the metal tray. This could be explained by the plastic tray height being higher than the metal tray height and the fact the soil surface in the first test was below the edge of the tray.

When simulating erosion in a wind tunnel, the length and height of the test section are important aspects of the infrastructure because they influence the boundary layer development and the achievement of the desired transport modes, such as equilibrium saltation, for example (BUTTERFIELD, 1999). In smaller test sections, transport by saltation, is usually promoted with the help of sediment feed mechanisms (BUTTERFIELD, 1999, HOUSER et al., 2001a) and the sediment is catched with passive or aspirated samplers (COPELAND et al., 2009). These types of equipment were not available for this study. In a different approach, DE VOS (1996) placed trays to cover a length of 15 meters which was an enough distance to the achievement of an equilibrium between falling and jumping soil particles, while VAN DIJK et al. (1996) used a distance of 7 meters but in a 20 meters long test section plus a collection chamber.

The tests with an extended collecting area that where implemented showed that most of the eroding particles deposited in the test section got collected in the first 100 cm (length of trays in first row), immediatelly downwind of the sample tray. In these runs the increase of sediment collected for velocities 10 and 13 m s^{-1} reinforced the need to test these conditions, while the length of the sample tray was irrelevant since there was no difference between its position being transversal (30 cm) or parallel to the flow (70 cm).

COPELAND et al. (2009) used a small tray (10 cm long) immediatelly downwind of the sample tray to collect creeping particles. The particles collected in the creeping tray were weighed and added to the mass collected in a saltation trap. This was considered the sediment loss by the tray, for the soil coarser fraction. A similar test was tried in the present study, but without the saltation trap. Instead of adding the collecting tray downwind, a separation was made in the sample tray. This was made because some of the sediment got lodged between trays in the previous experiments. The splitted tray (collecting and sample area) was proven to be a good way of collecting the sediment, with the length not being a determinant factor, since the additional tray (that covered the next downwind 30 cm) did not present almost any particles.

The visualization of the flow with the smoke machine and laser sheet allowed to understand the effects of the tray edge on the wind flow. To minimize the drag produced by the edge of the tray, instead of levelling the entire test section with the tray using a false floor (CORNELIS et al., 2003, CORNELIS et al., 2004) or making an opening to the wood floor itself, ramps were built to be placed close together with the upwind and downwind edge of the tray. In terms of the resources available and to change the wind tunnel main structure as little as possible, this was considered the best way to proceed.

Only one of the studies shown in table 2 (Section 2.2.2.) presented a tray with length below 50 cm. Although none of them mentioned any drawback related to this factor, the ramps were built to be applied with the larger metal trays whose length could be reduced, if needed, and also because the size enabled the inclusion of the collecting area. Also, since there were many available (contrarily to only one plastic tray), the empty space at both sides of the tray could be levelled with more trays turned upside down.

Taking into consideration the test section size left for the erosion simulation, the tray with collecting area for creeping particles was the only feasible way to collect the sediment. The possibility of extending the area after the test section to have a collection chamber and the construction of a sandtrap was also not feasible for the resources available. Therefore, in the methodology designed for the wind erosion experiment described in Chapter 3, a tray divided in sample area and area for collecting creeping particles was used.

In the majority of the studies used as base for this methodology definition, the dust fraction was quantified by using optical dust monitors that were able to count the eroded particles or estimate the dust concentration, and aspirated samplers containing filter holders where sediment got collected. For experiments implemented in this work, there was no visible dust cloud leaving the tray whether by direct visualization or by the laser sheet method, although there was biochar dust deposition on the laboratory, possibly indicating that the methodology (with adhesive surfaces and filter holders) used was not effective. This may have happened because if particles of this size encounter an object or obstacle in their way, they follow the flow lines due to their reduced inertia and do not impact with the obstacle.

Hot-wire anemometers (BUTTERFIELD, 1999, VAN PELT et al., 2013, ZHANG et al., 2012, ZOBECK et al., 2013) and vane-probe anemometers (CORNELIS et al., 2003, CORNELIS et al., 2004, ERPUL et al., 1998, ERPUL et al., 2002) are two examples of equipments applied in wind tunnel erosion studies which are used to control the wind flow velocity. Although these devices are commonly used, the Pitot tube anemometer (ALFARO & GOMES, 1995, RAVI et al., 2006, SHARRATT et al., 2010) was employed in the experiments because it is a more robust equipment to be used in erosion studies since particles could damage the hot-wire anemometer. Additionally, it was used in the majority of the methodologies that were found in the literature.

Different run durations were used in the experiments made for the method development. No reference was found on the best run time to use in the application of the method. The durations applied in other experiments varied considerably, as it is shown in Table 4.

Table 4. Run durations applied in other methodologies found in the literature.

Run time [min]	Method
2	CORNELIS et al. (2003)
3	CAMPBELL et al. (2002)
5	NICKLING et al. (1997)
6	FUNK et al. (2008)
7	LEYS et al. (1998)
9	SHAO et al. (1993)
10	SHARRATT et al. (2010)
15	LIU et al. (2006)
20	ZOBECK et al. (2013)

LIU et al. (2006) used 15 minute runs at 8 m/s to study the ridge-tillage effects on cropland. This was the run duration chosen for the experimental tests having in mind the general aim of this study and the fact that biochar is being applied to soil for crop yields improvement.

2.5. Conclusions

The objective identified in the Introduction was to test the DAO wind tunnel conditions for wind erosion studies and select a robust method to collect sediment emitted from wind erosion of soil, from the coarser particles to the dust fraction.

A wide number of methodologies to achieve this goal were found in the literature. The majority of the studies employed sand traps to collect the sediment transported by creeping and saltation modes or balances mounted in the tunnel test section that registered the weight loss continuosly. Other equipments, as optical monitoring devices or aspirated samplers are used to determine the concentration for the finer fraction of the eroded sediment.

The determination of the dust fraction emitted from the soil for the erosion simulations was not possible and the test section was not large enough to represent accurately the saltation condition. The only possible way to have information on the erosion of soil was to collect the creeping particles which account for the coarser fraction of the eroded sediment. This was done by dividing each tray in a sample area and a collecting area and adding two ramps upwind and downwind from it to minimize the effect of the tray edge.

Runs with the duration of 15 minutes and wind velocities around 6, 10 and at least 13 m s^{-1} should be used since these were the velocities for which the intensity of the erosion event showed to be significantly different between each other, considering the characteristics of the soil used in the experiments.

III WIND EROSION OF BIOCHAR-AMENDED SOIL – A WIND TUNNEL EXPERIMENT

3.1. Introduction

Wind erosion is an important land-shaping process that may exist in a wide range of environments, each one with its specific characteristics that influence particle entrainment and transport. Cold regions, beach dune systems and agricultural fields are examples of areas where wind erosion may occur (HAN et al., 2009, LIU et al., 2006, MCKENNA NEUMAN et al., 1989).

Between several factors that govern wind erosion, surface moisture is one of the most significant, because it promotes bonds that keep particles together through adhesion and capilary effects (MCKENNA NEUMAN et al., 1989). Particle movement will only start when destabilizing forces (i.e. drag forces, lift forces and aerodynamic moment forces) can overcome stabilizing forces (i.e. particle weight, interparticle and binding forces) (IVERSEN et al., 1976). This means that unless surface moisture content is taken into consideration it is not possible to correctly assess or predict wind erosion (CORNELIS et al., 2003).

CHEPIL (1956) was one of the first investigators to study the influence of soil moisture on resistance to wind erosion and reported that the degree in erodibility was directly proporcional to the adsorbed water content. BISAL & HSIEH (1966) concluded that 4 % could prevent erosion of fine sandy loam soil. BELLY & KADIB (1964) found mathematical relationships between MC and the TFV. MCKENNA NEUMAN et al. (1989) showed that most sand with a moisture content above 0.2 % would not be affected by wind. However differences and contradictions exist in the literature since the way wet particles begin to move are still unclear (CORNELIS et al., 2003).

Biochar is a predominantly stable organic material with recalcitrant properties, created when biomass is pyrolyzed to temperatures usually between 300 and 1000 ^{0}C (JEFFERY et al., 2011). This carbon-rich material is currently being considered as a means of mitigating climate change (by sequestering C) and also being able to improve soil properties and functions as discussed in Section 1 (JEFFERY et al., 2011). There are no experimental studies in literature where wind erosion induced by the aplication of biochar to soils has been investigated (VERHEIJEN et al., 2010). Biochar may be incorporated into the soil or applied to the soil surface and, if in the first case it does not present any harm, for the last case, there is an effective risk of erosion ocurring due to biochar relatively low density and, thus, higher erodibility (VERHEIJEN et al., 2010).

The objectives for the investigation described in this chapter were:

I. To evaluate the wind erosion potential of biochar-amended soil and to distinguish the contribution of both mineral and biochar particles.

II. To investigate the influence of biochar on the relationship between soil moisture content and wind erosion.

3.2. Methods and materials

3.2.1. Wind tunnel

Wind tunnel components

The analysis and interpretation of the results from the experimental work described in Chapter 2 helped to define the methodology used in the following study. The wind tunnel used for the experiments presented here, had a number of modifications compared to the representation in Figure 6, identified by oval shapes in Figure 12. The air, before entering the test section, passes by a setup of turbulence generators and floor roughness elements in order to establish the atmospheric boundary layer as in the surface of the Earth. The Pitot tube allows the measurement of the wind flow velocity and, downwind from it, is the area designed to receive the sample tray accompanied by the ramps.

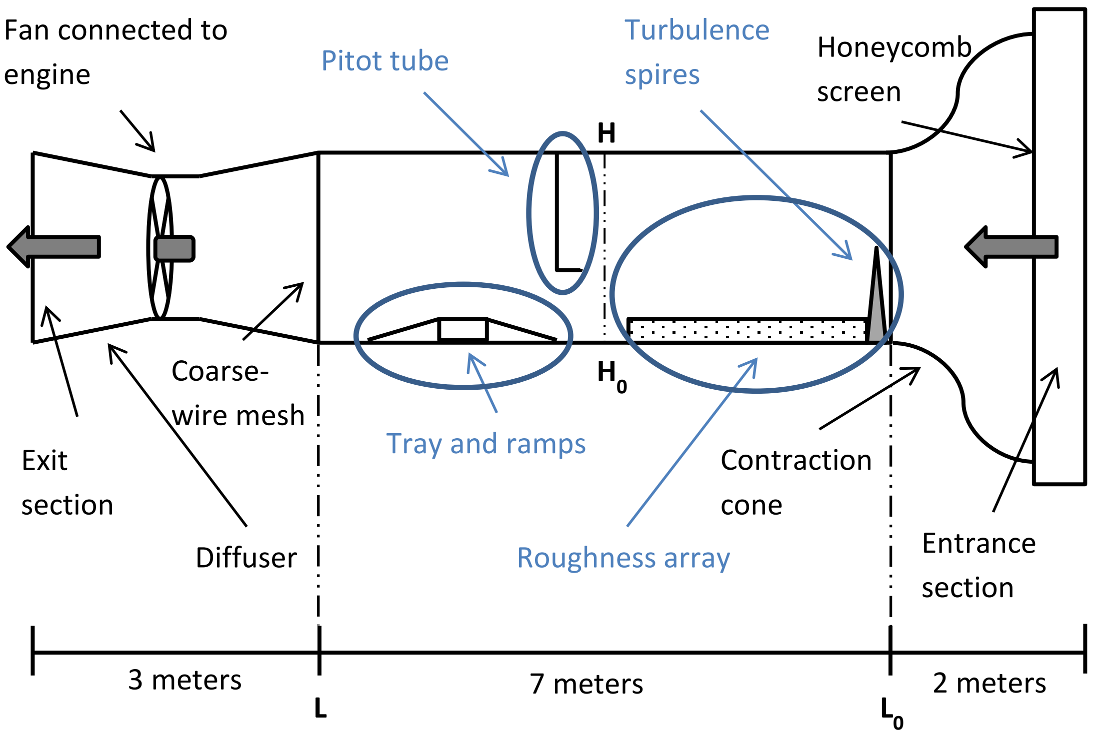

Figure 12. Schematic representation of the elements that compose the DAO wind tunnel after the methodology development (see Chapter 2). The Pitot tube, the tray setup and the roughness elements were added to the test section.

Experimental setup

The experimental setup was composed of roughness elements, five sample/collection trays, one wooden board, two ramps and one Pitot tube. The sample tray was installed in the middle of the test section (in terms of its width) with two trays upside down at the left and the right (see Figure 13). Next to this, there was a wooden board with the same length and height as the trays. This adaptation was necessary since it was impossible to have four trays, in parallel, levelled with the sample, which would leave an empty space in the setup. Possible disturbances to the wind flow induced by the surface unlevelling were, therefore, prevented. The ramps were built with the objective of minimizing the effect of tray borders on the wind flow, as discussed in Section 2.

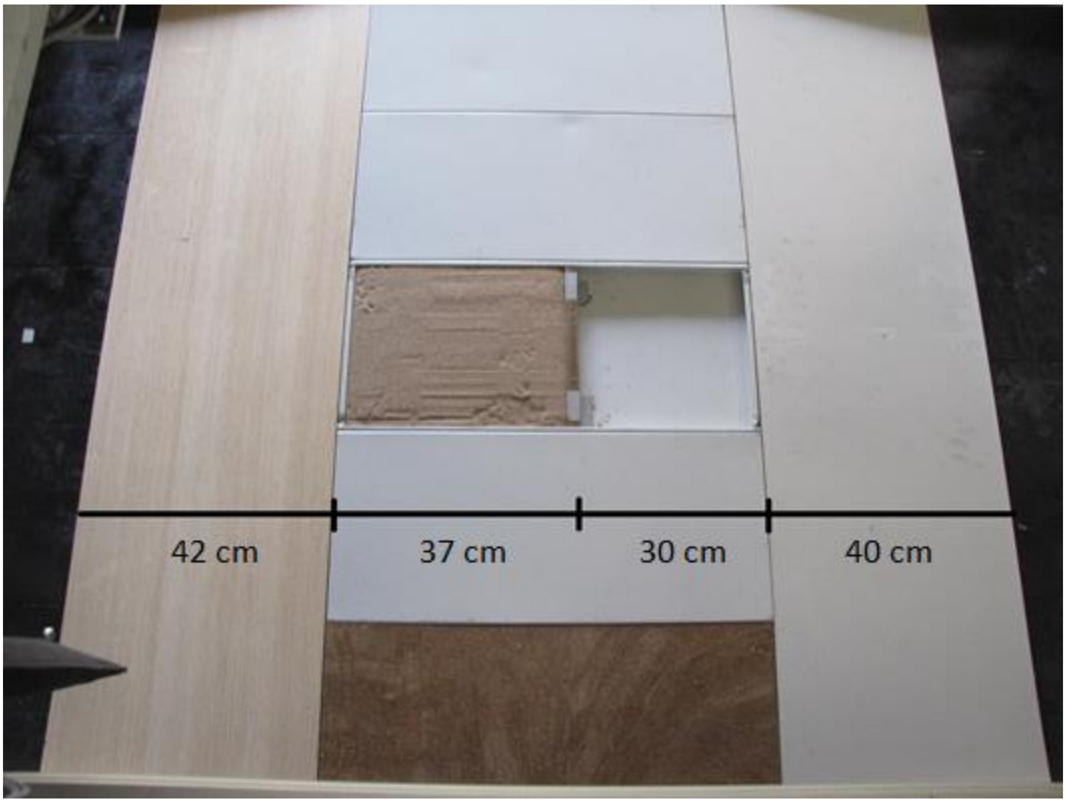

Figure 13. Tray setup with the two ramps by each side, the sample area and the collecting area immediately after.

Wind flow velocity measurements

The wind flow velocity inside the tunnel was measured with a Pitot tube as described in Section 2.2.1. Firstly, measurements were made to determine the wind velocity vertical profile across the boundary layer, until the free stream velocity was reached. The profile was obtained, above the middle of the sample tray (see Figure 14).

Figure 14. Pitot tube position for the determination of the velocity profile above the soil surface.

For normal atmospheric conditions on flat surfaces without vegetation and in neutral atmosphere, the velocity profile plots as a straight line on a semi-logarithmic chart (ARGAMAN et al., 2006). The gradient of the semi-logarithmic profile is a consequence of the drag caused by the surface roughness on the airflow and is usually described in terms of the friction velocity u^*, as shown in equation 1 (ARGAMAN et al., 2006). The aerodynamic roughness length z_0 is related to the height of the surface roughness at which the wind velocity assumes the value of zero (BLUMBERG & GREELEY, 1993). This parameter also influences the gradient of the velocity profile and, consequently, u^*.

Equation 1 may be approximated by a least-squares curve fitting method (equation 3) (DONG et al., 2003, ZHANG et al., 2004) which, then, enables the determination of u^* and z_0 (equation 3 and 4), if the variation of velocity with the test section height is known. This method was applied, using the values for the velocity determined by the Pitot tube and the respective height, and is represented by

$$u(z) = b + m \times ln(z) \qquad \text{Equation 3}$$

where *m* and *b* are regression constants.

The friction velocity u^*, is obtained by

$$u^* = k \times m \qquad \text{Equation 4}$$

while the aerodynamic roughness z_0 is obtained by

$$z_0 = \exp\left(-\frac{b}{m}\right) \qquad \text{Equation 5}$$

The thickness of the boundary layer, considered as the height at which the wind velocity is 99% of the free stream velocity, was also determined.

3.2.2. Soil sampling and pretreatment

The soil used in this work is a Haplic Arenosol Dystric (IUSS, 2006) sampled from the inner-dune complex of Dunas de Vagos, which belongs to the coastal region of Aveiro, Central Portugal. The coordinates are 44^0 42' N and 8^0 42' W, approximately 10 km south of the city of Aveiro and 6 km from the Atlantic Ocean (KEIZER et al., 2005). This area hosts a plantation of *Eucalyptus globulus Labil* and presents reduced ground cover as well as reduced litter accumulation (KEIZER et al., 2005). The climate is classified as subhumid meso-Mediterranean with a mean annual temperature around 15^0C and mean annual rainfall of approximately 950 mm (DRARN-CENTRO, 1997).

Disturbed soil samples were taken from the field site to an approximate depth of 20 cm, using a pickax and shovel. Around 200 kg of soil were collected into plastic bins and brought to the DAO wind tunnel laboratory. The soil was sieved over 2 mm to allow the removal of some organic debris and stones. The soil fraction smaller than 2 mm was spread out on a plastic sheet to accelerate the drying process and to facilitate the sieving to smaller particle sizes. Subsequently, the soil was spread out to air-dry at ambient temperature in a maximum 5 cm thick layer inside cardboard boxes in a closed laboratory. During the following days, the soil was stirred manually in order to obtain a homogeneous drying. After achieving the air-dry soil condition, it was stored in plastic bins. During the wind tunnel work, all of the stored soil, whether being pre-treated or not, was protected with plastic covers to minimize external interferences.

3.2.3. Soil and biochar characteristics

Biochar bulk density, electrical conductivity (EC) and pH were determined as it is described in the website of the European Biochar Certificate Foundation, a group of industrial standard procedures developed by scientists, based on the latest scientific data. The protocol used for biochar bulk density determination is VDLUFA-Method A 13.2.1 (Association of German Agricultural Analytic and Research Institutes – VDLUFA). As for EC and pH, since the protocols available in EBC website derive from the DIN ISO 11265 (1997-06) (German standard of ISO 11265:1994) and DIN ISO 10390:2005 (German standard of ISO 10390:2005), respectively, and both are for soil quality, the determination of the sampled soil EC and pH followed the same procedures as for the biochar.

The biochar used in this experiment comes from a woody feedstock, which is commonly used since lignocellulosic biomass is a natural abundant material. In addition these are biochars that provide more water retention and are mechanically strong (VERHEIJEN et al., 2010). In order to determine biochar bulk density (see Table 6), a sample was filled into a graduated cylinder and, then, its mass was determined. Three replicates were made with different volumes: 260, 360 and 480 mL. As for the bulk density of the two types of samples, control soil and biochar-amended soil (see Table 5 and 6), the samples were prepared, following the same preparation procedure that was applied in the wind tunnel simulations (described in detail in Section 3.2.3). For simplification purposes, from now on, the control soil and biochar-amended soil are refered as control and mixture, respectively.

After being placed in plastic bags, both samples (mixture, air-dried, with a biochar concentration of approximately 10% w w^{-1}; and control, also air-dried) were filled into the metal tray selected for the wind erosion experiments. This concentration was at the higher end of biochar application rates in the literature (JEFFERY et al., 2011) which, in the case of an erosion event, may also present the highest sediment loss observable. The mass of sample that remained in the bag was subtracted from the total sample mass, giving the weight of sample in the tray. The volume occupied by the sample was determined by measuring the tray dimensions with a ruler: 37.0 x 29.0 x 3.4 cm (L x W x H).

Table 5. Bulk density of the mixture prepared in a similar way as for the wind tunnel runs, with a biochar concentration of ≈10%.

Mass						**Volume**	**Bulk density**
Tray	**Soil**	**Biochar**	**Mixture**	**Mixture remaining in bag**	**Mixture in tray**	**Tray**	**Mixture**
[kg]						**[L]**	**[kg L^{-1}]**
2,0430	4,5500	0,4550	5,0050	1,2400	3,7650	3,6482	1,0320

EC and pH were determined with the same procedure for both biochar and air-dried soil (Table 6). For EC, a 20 g mass from the sample was added to 200 ml demineralised water and shaken for 1 hour. After this, the sample was filtrated and the EC measured in the filtrated water with a Hanna HI 991300 pH/EC/TDS/temperature meter. The pH was determined by adding 5 mL of sample to five times this volume (25 mL) of a 0.01 M $CaCl_2$ solution. The sample was then shaken during 1 hour and the pH was measured directly with the same equipment as for the EC.

Table 6. EC, pH and bulk density for control soil and biochar. Biochar EC, pH and bulk density were determined following the DIN ISO 11265, DIN ISO 10390:2005 and VDLUFA-Method A 13.2.1, respectively. The same procedure used in the mixture bulk density determination was used for the control while EC and pH followed the same protocols as for biochar.

Material	Electrical conductivity		pH		Bulk density
		SD		SD	
	[µS cm^{-1}]				[g L^{-1}]
Control soil	38	11	4,71	0,03	1557
Biochar	1496	43	8,13	0,04	184

In tables A1.1, A1.2 and A1.3 it is shown the data used to determine the bulk densities and in A1.4, A1.5, A1.6 and A1.7 the data for EC and pH determination (see Annex 1).

The soil texture (air-dried) and biochar particle size distribution were obtained by sieving with a Retsch mechanical sieve shaker and Retsch sieves (Retsch GmbH and Co. Kg, Hann, Germany) and are presented in Tables 7 and 8, and Figures 15 and 16. As many size classes as possible (considering the available sieves) were used to characterize the coarser particle size classes of this sandy soil: 2000, 1400, 1000, 710, 500, 250 and 53 µm. The silt and clay fraction were considered as the mass fraction below 53 µm. For biochar, which presented a large particle size range, the sieves used were 5000, 4000, 3150, 2000, 200 and 50 µm. Four replicates were made for a 10 minute sieving period.

The soil used in the experimental work presents a texture where almost 80% of the mass is included in the fractions 500-710 and 710-1000 µm (see Table 7 and Figure 15).

Table 7. Soil texture of the soil used in the experimental tests, in terms of mass percentage; n = 4; SD = standard deviation. Before this characterization the soil was air-dried and, then, sieved for organic matter removal.

Silt and Clay	Sands						
< 53 µm	53 - 250 µm	250 - 500 µm	500 - 710 µm	710 - 1000 µm	1000 -1400 µm	1400 - 2000 µm	> 2000 µm
% Mass							
0,75	13,86	50,05	26,65	7,77	0,83	0,06	0,01
SD							
0,00	0,01	0,04	0,34	0,56	0,71	0,21	0,06

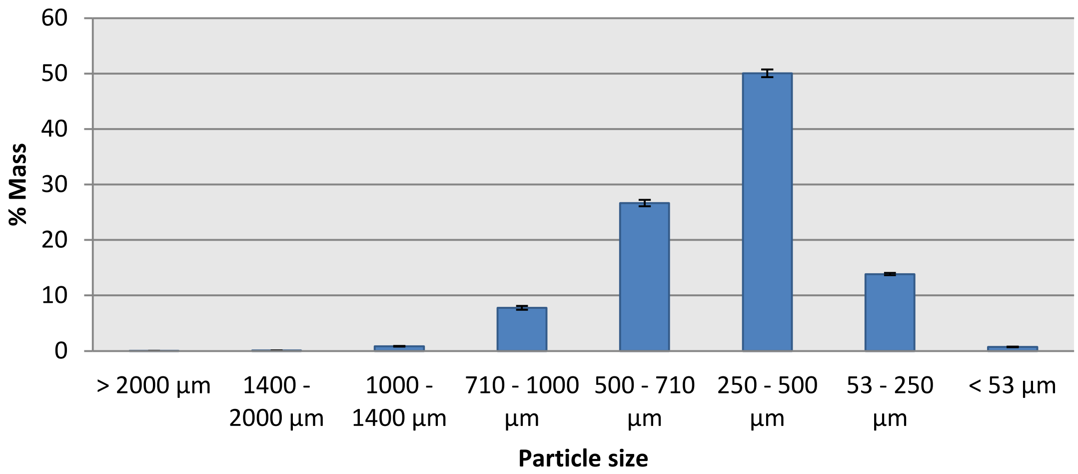

Figure 15. Graphical representation of the sandy soil mass percentage for each particle size.

As for the biochar particle size distribution, the highest mass percentage was observed on the class 200-2000 µm. The data for determination of the soil texture and particle size is shown in Annex 1.

Table 8. Biochar particle size distribution (gravimetric). Biochar was air-dried before the characterization; n = 4; SD = standard deviation.

Aggregate size						
< 50 µm	**50 - 200 µm**	**200 - 2000 µm**	**2000 - 3150 µm**	**3150 - 4000 µm**	**4000 - 5000 µm**	**> 5000 µm**
% Mass						
1,84	5,35	32,31	18,51	11,51	11,61	18,87
SD						
0,90	0,84	8,45	3,82	1,70	1,39	2,73

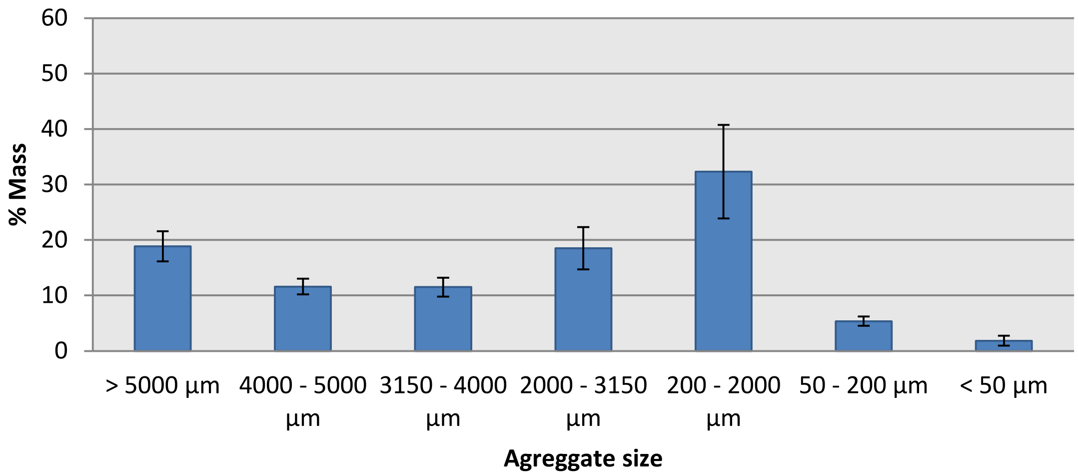

Figure 16. Graphical representation of the biochar mass percentage for each particle size category.

3.2.4. Soil and biochar mixing and equilibration

Soil and biochar required quantity

The test tray was fitted with a fixed wooden barrier (3 cm thick) separating the collection area from the area designed for the soil sample. After filling up the sample area of the test tray, so that it was levelled with the borders, the soil was removed and weighed on a balance. This is the mass of soil necessary to prepare the control sample.

Following the last step, biochar was added to achieve 10% gravimetric concentration (w w^{-1}) which is close to the higher end of biochar application rates described in the literature (JEFFERY et al., 2011). The mixture was put in aluminum trays and placed in the oven at 105 ^{o}C for 24 hours. After stabilizing in the desiccator for 1 hour, the mixture was spread out in the test tray and levelled the same way as in the first step. The mass of the remaining biochar was subtracted from the total amount to know the mass necessary for the samples of biochar-amended soil. In the end, to prepare a control sample, the mass of air-dried soil was approximately 6 kg. To fill the same volume with biochar-amended soil at air-dried condition, the mass available for the mixture should not be more than 5 kg.

Sample preparation at the desired moisture content

After the preparation of the samples was finished, the air-dry moisture content (MC) was determined for the soil and biochar-amended soil samples. With this information and taking into account similar studies relating the influence of moisture in soil erosion by wind processes, the MC range was selected at: 1.7% (MC for biochar-amended soil at air-dried temperature), 4.0% and 8.0%, with 3 replicates for each one (similar range as, for example, CHEN et al. (1996), FUNK et al. (2008), ZHANG et al. (2012)). The soil presented a MC of 0.2% (air-dried) so it appeared reasonable to increase it to 1.7%. To obtain the higher MCs, firstly, the mass of water to be added was calculated and determined in terms of its volume (see Table 9), assuming that the density of distilled water is approximately 1 kg L^{-1}. This volume was added using a measuring beaker and a vaporizer from a spray bottle into a large bag holding the sample (CORNELIS et al., 2003, HAN et al., 2009), which was positioned to prevent water losses on the bag's upper surface and to allow a better way of mechanically homogenizing the mixture. Each bag was placed in a refrigerator at 4 ^{0}C for 24 hours to allow equilibration of the sample. Additional data used for sample preparation is shown in Annex 2.

Table 9. Mass of water to be added for each type of soil to achieve the target moisture content. For the mixture at 0.21%, water was added to oven-dried biochar which was left to equilibrate for 24 hours and, then, mixed with soil. The remaining initial MC refers to the air-dried condition.

Type of soil	Total sample mass [kg]	Initial MC	Target MC	Volume of H_2O added [mL]
Mixture	5	0,00%	0,21%	1
		1,71%	4,00%	108
		1,71%	8,00%	286
Control	6	0,21%	1,71%	88
		0,21%	4,00%	218
		0,21%	8,00%	432

The biochar and soil quantities, volume of water added and equilibration period for the sample preparation described above are organized in the flow chart presented in Figure 17.

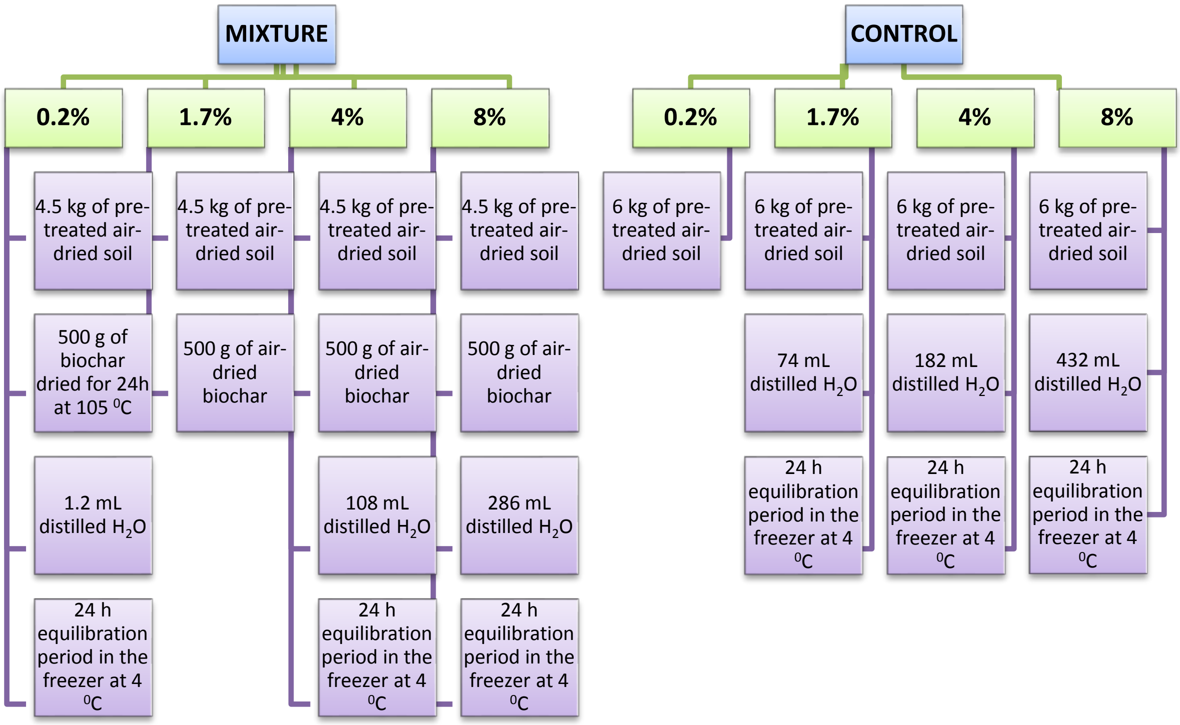

Figure 17. Flow chart of the sample preparation between different moisture contents

In Annex 5, a protocol for the preparation of the samples at each moisture content is presented.

3.2.5. Simulation of the wind erosion event

After the equilibration period, the sample was moved from the large plastic bag to the sample area in the metal tray with the use of a soil scoop. The biochar-amended soil was stirred before taking a scoop in order to sample the material as homogenized as possible. To achieve representative sampling, it was imperative that the samples were taken randomly-spaced and not only from the soil upper layer. When laying the soil in the tray attention was paid to prevent the biochar (especially, the large particles) from occupying the sample top layer while the mineral soil remains in the bottom layer.

While placing the soil/biochar in the tray, the material was pressed with the scoop or using the hands (with gloves) to help flatten the surface and reduce surface roughness. After having sufficient soil, with none of the tray borders above the soil surface, another flat surface (e.g. the bottom of another tray) was pressed against the soil surface. Finally, it was necessary to check if the entire surface was well flattened: a thin metal ruler was used in this study (ARGAMAN et al., 2006). With the biochar-amended soil it was impossible to sweep the surface due to biochar particles. Because biochar has lower bulk density and higher particle size range (that can go up to a few cm) than soil, more biochar particles left the tray when the surface was being flattened, leaving large holes where particles used to be. Therefore, the ruler's thinner part was positioned throughout the tray length and soil was added to the places where it was missing (below the ruler). The collection area of the tray was covered to prevent any particle jumps to this section while preparing the samples.

A Pitot tube located between the tray/ramp setup and the roughness array allowed the wind velocity control and, before inserting the sample tray, the engine was turned on and the frequency equivalent to the desired velocity was checked. This procedure was made with a tray upside down where the sample tray was placed before the run start. After defining the frequency, the sample was placed in the wind tunnel setup as shown in Figure 13. The elements should stay as close as possible to obtain a levelled surface throughout the entire setup. Once the tunnel door was closed, the engine was turned on to achieve a 7 m s^{-1} free stream velocity condition, which was re-checked with the manometer after the run started. This wind velocity is at the lower range of the tested velocities and it was applied in other similar erosion studies, already mentioned in Section 2. It is also not far from the value of 5 m s^{-1}, considered as the threshold for pedestrian use of outdoor spaces (AMORIM et al., 2014). The run duration considered was 15 minutes and after this period the tray was taken outside the tunnel so that the sediment could be collected.

All the sediment in the collecting area was stacked to one side with the help of a small brush. Then, using an aluminum sheet taped to the tray bottom with an adhesive tape stripe, on the other side, the sediment was once more brushed, but now to the sheet. In the end, the sediment was transferred to plastic bags which were closed, tagged and stored. The samples of collected sediment were placed in crucibles, oven-dried at 105 ^{0}C for 24 hours and, after stabilizing in the desiccator for 1 hour, their mass was determined by weighing.

3.2.6. Statistical Analysis

The statistical analysis of the data obtained from the wind erosion tests for both types of soils was performed using Sigma Plot version 11.0 for operating system Windows 7. One-way ANOVAs followed by the Tukey Test (Multiple Comparisons) were performed to test significant difference in sediment loss, between moisture contents, for the biochar-amended soil. Krustall-Wallis procedure (one-way analysis of variance), also followed by Tukey test, tested significant difference in sediment loss, between moisture contents, for the control soil. T-tests and Mann-Whitney tests were also used to understand the presence of significant differences between the same moisture contents for both control and biochar-amended soil.

3.3. Results

The wind velocity profile obtained above the soil surface is presented in Figure 18. The free stream velocity was observed at the height of 37.5 cm with the value of 7 m s^{-1}. This group of values correspond to the moment when the wind velocity stabilized along the profile. The boundary layer thickness was 34 cm. The initial height corresponds to 1 cm above the height of the tray surface (3.5 cm). The information used to determine the wind velocity profile is shown in Table A3.1 (Annex 3).

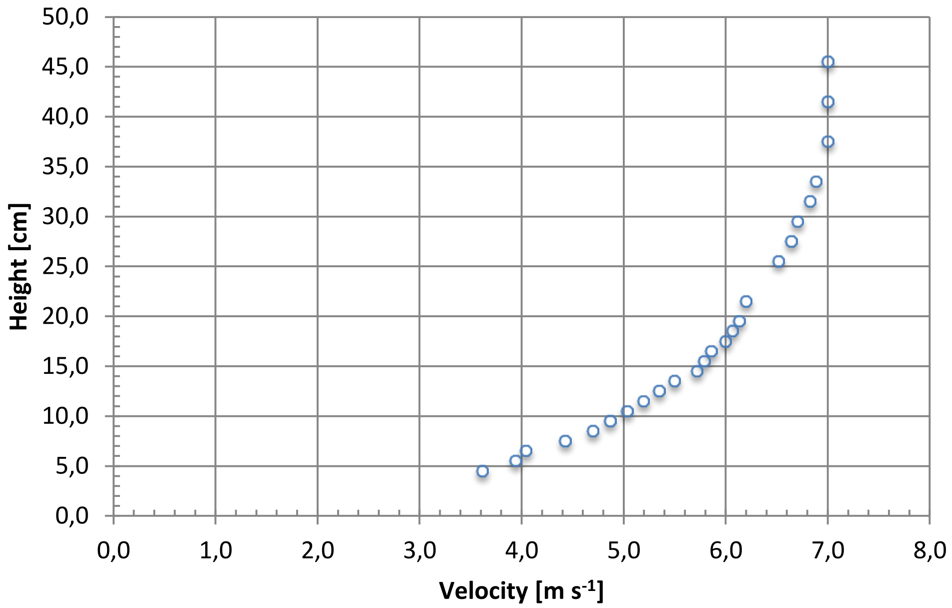

Figure 18. Wind velocity vertical profile above the soil surface.

The results of the least mean squares fitting method are presented in Figure 19. It is observable that the relationship between the natural logarithmic value of height and velocity is well aproximated by the linear curve (y = 1.5839x + 1.3172; R^2 = 0.9851). With this information it was possible to determine an approximation of the friction velocity at the soil surface for the corresponding free stream velocity of 7 m s^{-1}. The friction velocity obtained for this condition was 0.634 m s^{-1}. The approximation for the aerodynamic roughness (or the height at which wind velocity is considered zero) was 0.435 cm.

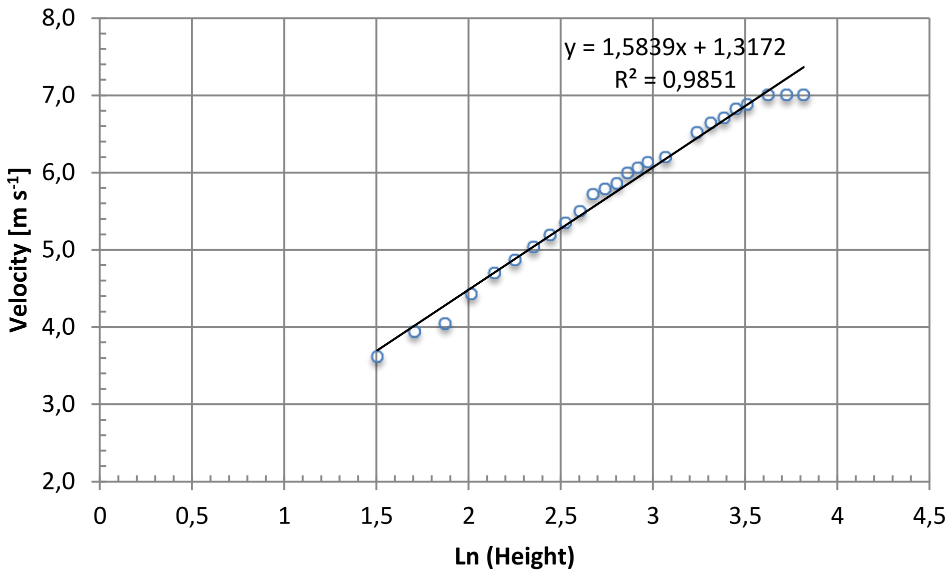

Figure 19. Application of the least squares fitting method to the values of the vertical profile above the soil.

In the sediment loss, for each moisture content in separate, between mixture and control soil, the difference in the mean values of every pair of groups was greater than would be expected. This shows that there was a statistically significant difference between control and mixture for the same moisture content in sediment loss. In Figure 21, the mean values marked with “*” refer to a p-value less than 0.01 while for mean values marked with “‡” the p-value was less than 0.001, for a significance level of 0.05.

An example of the collected sediment is shown in figure 20. The mass of sediment that left the tray for biochar-amended soil and control soil with each moisture content is shown in Figure 21.

Figure 20. Sediment collected after an erosion simulation.

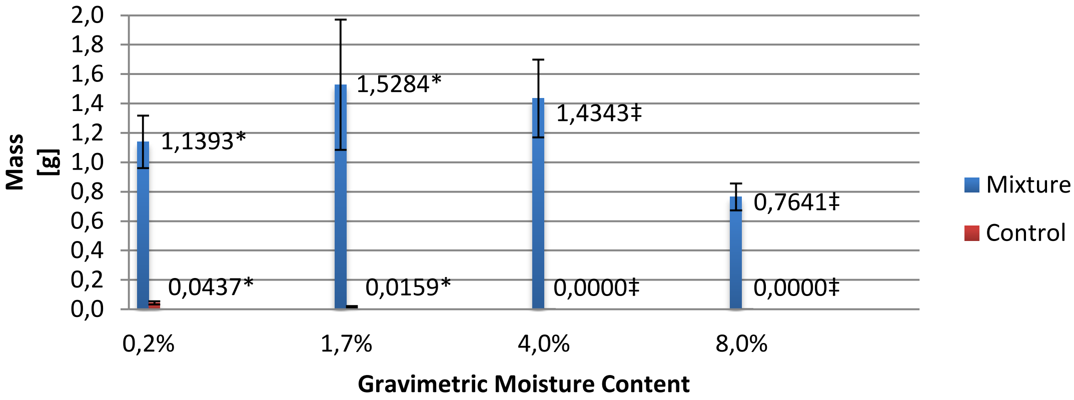

Figure 21. Mass of sediment loss, in g, for the two type of soils, mixture and control, between the different moisture contents: 0.2, 1.7, 4.0 and 8.0%. * = p-value < 0.01; ‡ p-value < 0.001; for a significance level of 0.05.

The one-way ANOVAs and the Krustall-Wallis H-test procedure (one-way analysis of variance) showed that there was significant difference between moisture contents for sediment loss in both mixture and control, separately (see Table 10). The values of F (ANOVA) and H (Krustall-Wallis) underlined in Table 10 refer to significant differences between moisture contents at the significance level of 0.05.

Table 10. One-way ANOVA (mixture) and Krustall-Wallis test (control) results. Df = degrees of freedom. Underlined values are significantly different.

Source	Df	Sediment loss
Moisture content		
Control	3	7,737
Mixture	3	18,348

Results from the Tukey tests for the mean values obtained in sediment loss for control and mixture are presented in Tables 11 and 12, respectively. The letters “a”, “b” and “c” denote statistically significant groupings of mean values within sediment loss. The same letters indicate that means in that group are not significantly different, at the significance level of 0.05.

Table 11. Sediment loss, in g, for control samples at different moisture contents. a, b, c = significant groupings of mean values; same letters indicate there is no significant difference.

Moisture content	Sediment loss
%	[g]
0.2	0,0437 a
1.7	0,0159 ab
4.0	0,0000 bc
8.0	0,0000 bc

Table 12. Sediment loss, in g, for mixture samples at different moisture contents.

Moisture content	Sediment loss
%	[g]
0.2	1,1393 ab
1.7	1,5284 a
4.0	1,4343 ab
8.0	0,7641 b

3.4. Discussion

The wind velocity profile obtained above the surface showed that the condition of turbulent wind flow was achieved. This means that the turbulence spires and the roughness arrays were able to transform the uniform flow into turbulent flow correctly and the conditions observed at the surface boundary layer of the planet were well simulated (IRWIN, 1981). It also shows that the instalation of the ramps did not present any major interference with the wind flow. COPELAND et al. (2009) determined the friction velocity (0.48 m s^{-1}) and aerodynamic roughness (0.236 cm) of soil with wood strands (similar surface cover as the woody feedstock biochar used) for a similar wind velocity (6.5 m s^{-1}) The friction velocity obtained for the present study (0.63 m s^{-1}) was in a similar range but higher when compared with the study of COPELAND et al. (2009). However, to compare both values, a more accurate velocity measurement (stack of Pitot tubes or hot-wire anemometer) should be used to determine the velocity profiles continuously as the run takes place (BUTTERFIELD, 1999) The aerodynamic roughness was considerably higher for the present study (0.435 cm) when compared to the study of COPELAND et al. (2009). However one cannot really establish a comparison between these values because of the differences in particle shape (particularly height) which influence greatly the aerodynamic roughness (ZHANG et al., 2004).

Differences on the magnitude of the erosion event were observed between the control soil and mixture soil. The statistical analysis confirmed that there were significant differences between each type of soil for the same test conditions. When compared to experiments with control soil where almost no sediment was collected, for biochar-amended soil there was considerable movement of sediment out of the tray. Although this sediment left the sample tray, it was mostly composed by biochar particles, which could be easily distinguished from some few small mineral grains, in the collecting tray.

If at 0.2% and 1.7 % MC there were, in fact, some visible grains, at the higher moisture contents only biochar particles were collected. This was in agreement with the tests for control soils where a small portion of mineral particles were collected for the lower MCs (0.2 and 1.7 %), while for the higher MCs particles did not erode. As for biochar particles, since they have a lower bulk density than soil particles they are, naturally, more predisposed for being transported. According to other studies observed in the literature, the wind velocity at which the tests were performed is on the lower end of the ranges commonly used (ARGAMAN et al., 2006, BUTTERFIELD, 1999, CHEN et al., 1996, COPELAND et al., 2009, LU et al., 2013). This may indicate the need for the actual parameters to be tested at higher wind velocities (as it was mentioned in Chapter 2), in order to have a more effective erosion condition.

Although there was a need to test higher velocities, the results still gave information on the effect of the moisture content on sediment entrainment. The statistic analysis showed that there was significant differences on eroded sediment, due to moisture content. The Tukey test compared multiple pairs of means within groups (control and mixture) and for mixture there was significant difference between 1.7 and 8.0 % MC in sediment loss. As for the control 0.2 %, it was considered significantly different from 4 and 8 % also for sediment loss, even though a small number of particles left the tray. This proves a significant reduction particularly for experiments on biochar-amended soil.

Despite this reduction, there was still erosion of biochar, which also indicates that a higher moisture content should be tested to determine the threshold after which erosion stops. The biochar produced from woody feedstocks has a more porous structure and, consequently, large inner surface which favours water retention (VERHEIJEN et al., 2010). This factor also influences the reduction on erosion since a higher mass of water contained in biochar particles may increase the particle weight, being necessary more energy to move it.

Moisture content may also influence the biochar particle mobility in soil, since with an increase in MC a more homogeneous mixture was obtained in the sample tray. For lower MCs the biochar lower bulk density makes particles to stay preferencially at the surface, while heavier soil particles remain in the bottom. The hypothesis that biochar may improve soil aggregation acting as a binding agent (VERHEIJEN et al., 2010) could influence the way particles move within the soil or if they are more able to be detached from the surface. VERHEIJEN et al. (2010) states that “biochar can affect soil aggregation due to interactions with SOM, minerals, and microorganisms" but this depends on biochar surface charge characteristics and how they develop along the time. Aged biochar normally has a high CEC which then increases its potential to act as a binding agent of organic matter and minerals (VERHEIJEN et al., 2010).

Although the effect of moisture content on biochar-amended soil was not tested for higher wind velocities, the behaviour of these particles under these experimental conditions indicates that it is not necessary to have a wind velocity characteristic of an intense erosion event to biochar particles suffer erosion.

Aditionally to the variation of the MC and wind velocity, future studies may go even further and investigate the influence of biochar from different types of feedstock, different biochar concentrations and also particle sizes.

3.5. Conclusions

The objectives identified in the Introduction were: (I) to evaluate the wind erosion potential of biochar-amended soil (including relative contributions of mineral and biochar particles); and (II) to investigate the influence of biochar on the relationship between soil moisture content and wind erosion.

Almost exclusively biochar particles were displaced and the lack of mineral sediment loss indicates that higher velocities should be tested to have a condition where bare soil may be compared with biochar-amended soil. Additionally, it was also not possible to find the threshold moisture content which may indicate that a higher level should have been used. The free stream velocity selected to perform the methodology was 7 m s^{-1}, representative of a small erosion event. Medium and high erosion events were not possible to do taking into consideration the duration available for the experiments.

Erosion of biochar-amended soil was similar for 0.2%, 1.7%, and 4.0% MC. A significant reduction in erosion (ca. 50%) of biochar-amended soil occurred at 8% MC. Since greater MCs were not tested, it is not possible to determine at what MC erosion would stop completely. Assuming a linearity, a cessation of erosion may occur around 12% MC. Future work is recommended to identify if, and where, this threshold may occur. In the case of mineral particles, although higher velocities should be tested to have an effective erosion condition and to understand their interaction with MC, a threshold for the movement stop of mineral particles at 7 m s^{-1} was observed at 4 % since no particle got collected.

IV CONCLUDING REMARKS

The effects of soil erosion go beyond the loss of fertile land. It has led to increased pollution and sedimentation in streams and rivers, clogging these waterways and causing declines in fish and other species. Winds may erode, transport, and deposit materials, and are effective agents in regions with sparse vegetation and a large supply of unconsolidated sediments (LAL, 1994).

The biochar concept has a strong global context and it is positioned strongly in the context of climate change (carbon abatement), but intrinsically linked to renewable energy capture (biomass pyrolysis), and food production and land-use change (food and feed production) (SOHI et al., 2010). The application of biochar to soils has been suggested as a way to improve agricultural productivity, combat land degradation and climate change. However the total extent of possible interactions between biochar and soil functions has not been fully understood, yet. Application of biochar to soils in conditions where erosion by wind may exist puts biochar as a possible inducing agent of threats to soil and investigation regarding this issue is still lacking.

The aim of the present study was to investigate the wind erosion potential of biochar amended-soil with a focus on the effect of soil moisture content, using a laboratory wind tunnel and the following objectives were established.

I. To evaluate the wind tunnel conditions for wind erosion studies;

II. To develop a wind tunnel methodology for investigating soil erosion by wind;

III. To use the developed methodology to study wind erosion of bare soil and biochar-amended soil at a range of moisture contents.

Although there was no availability on equipments usually employed for collecting eroded sediment, it was possible to implement an investigation in the DAO wind tunnel. The methodology developed in Chapter 2 allowed the investigation of one part of the aeolian processes (creep) and for a wind velocity typical of low intensity erosion events, the biochar particles are detached from the soil surface while the mineral particles stay still.

The soil moisture content was observed to have influence in the sediment loss of biochar-amended soil. However, further investigation is needed to understand the biochar behaviour for more intense erosion conditions and to determine the threshold moisture content for which erosion ceases to exist. This may help to gather more information on the effects of biochar application to soil functions, as well as the behaviour and fate of this material, which is indispensable to the definition of policies and regulations for its application.

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ANNEXES

Annex 1

In Annex 1 the determination of the mixture, biochar and soil characteristics is shown.

Table A1. 1. Biochar bulk density, in g L^{-1}.

Biochar					
Rep	**Volume**	**Mass**	**Bulk density**	**Average bulk density**	**SD**
	mL	**g**	**g L^{-1}**		
1	260	46,91	180		
2	360	68,00	189	184	4
3	480	87,94	183		

Table A1. 2. Mixture bulk density, in kg L^{-1}.

Mass						**Volume**	**Bulk density**
Tray	**Soil**	**Biochar**	**Mix**	**Mix remaining in bag**	**Mix in tray**	**Tray**	**Mix**
[kg]						**[L]**	**[kg L^{-1}]**
2,043	4,5500	0,4550	5,0050	1,2400	3,7650	3,6482	1,0320

Table A1. 3. Soil bulk density, in kg L^{-1}.

Mass			**Volume**	**Bulk density**
Soil	**Soil remaining in bag**	**Soil in tray**	**Tray**	**Soil**
[kg]			**[L]**	**[kg L^{-1}]**
7,0760	1,3960	5,6800	3,6482	1,5569

Table A1. 4. Determination of biochar pH.

Biochar				
Rep	**Temperature °C**	**pH**	**Average pH**	**SD**
1	21,7	8,16		
2	21,3	8,09	8,13	0,04
3	21,8	8,13		

Table A1. 5. Determination of soil pH.

Soil				
Rep	**Temperature °C**	**pH**	**Average pH**	**SD**
1	26,4	4,71		
2	26,0	4,74	4,71	0,03
3	26,4	4,69		

Table A1. 6. Biochar electrical conductivity, in µS cm^{-1}.

Biochar				
Rep	**Temperature °C**	**EC µS cm^{-1}**	**Average EC**	**SD**
1	21,7	1496		
2	21,3	1538	1496	43
3	21,8	1453		

Table A1. 7. Soil electrical conductivity, in µS cm^{-1}.

Soil				
Rep	**Temperature °C**	**EC µS cm^{-1}**	**Average EC**	**SD**
1	25,2	50		
2	25,3	30	38	11
3	24,9	34		

Table A1. 8. Texture characterization for soil in terms of mass percentage, replicate 1.

Particle size	Replicate	Mass					Fraction	Sediment loss
		Total before sieving	Sieve	Sieve plus sediment	Sediment	Total after sieving		
		g					%	
> 2000 µm	#1	193,68	387,27	387,3	0,03	193,67	0,02	0,01
1400 - 2000 µm			366,67	366,78	0,11		0,06	
1000 - 1400 µm			352,59	354,3	1,71		0,88	
710 - 1000 µm			324,48	340,34	15,86		8,19	
500 - 710 µm			310,28	363,02	52,74		27,23	
250 - 500 µm			292,38	387,84	95,46		49,29	
53 - 250 µm			264,44	290,73	26,29		13,57	
< 53 µm			246,24	247,71	1,47		0,76	

Table A1. 9. Texture characterization for soil in terms of mass percentage, replicate 2.

Particle size	Replicate	Mass					Fraction	Sediment loss
		Total before sieving	Sieve	Sieve plus sediment	Sediment	Total after sieving		
		g					%	
> 2000 µm	#2	215,97	387,27	387,29	0,02	215,95	0,01	0,01
1400 - 2000 µm			366,65	366,81	0,16		0,07	
1000 - 1400 µm			352,59	354,3	1,71		0,79	
710 - 1000 µm			324,48	340,37	15,89		7,36	
500 - 710 µm			310,25	366,29	56,04		25,95	
250 - 500 µm			292,37	402,51	110,14		51,00	
53 - 250 µm			264,43	294,75	30,32		14,04	
< 53 µm			246,24	247,91	1,67		0,77	

Table A1. 10. Texture characterization for soil in terms of mass percentage, replicate 3.

Particle size	Replicate	Mass					Fraction	Sediment loss
		Total before sieving	Sieve	Sieve plus sediment	Sediment	Total after sieving		
		g					%	
> 2000 µm	#3	200,76	387,26	387,28	0,02	200,75	0,01	0,00
1400 - 2000 µm			366,68	366,79	0,11		0,05	
1000 - 1400 µm			352,58	354,28	1,7		0,85	
710 - 1000 µm			324,45	340,17	15,72		7,83	
500 - 710 µm			310,26	363,4	53,14		26,47	
250 - 500 µm			292,34	392,73	100,39		50,01	
53 - 250 µm			264,44	292,49	28,05		13,97	
< 53 µm			246,25	247,87	1,62		0,81	

Table A1. 11. Texture characterization for soil in terms of mass percentage, replicate 4.

Particle size	Replicate	Mass					Fraction	Sediment loss
		Total before sieving	Sieve	Sieve plus sediment	Sediment	Total after sieving		
		g					%	
> 2000 µm	#4	173,97	387,26	387,29	0,03	173,94	0,02	0,02
1400 - 2000 µm			366,67	366,79	0,12		0,07	
1000 - 1400 µm			352,57	353,99	1,42		0,82	
710 - 1000 µm			324,49	337,92	13,43		7,72	
500 - 710 µm			310,24	357,13	46,89		26,96	
250 - 500 µm			292,29	379,1	86,81		49,91	
53 - 250 µm			264,42	288,5	24,08		13,84	
< 53 µm			246,23	247,39	1,16		0,67	

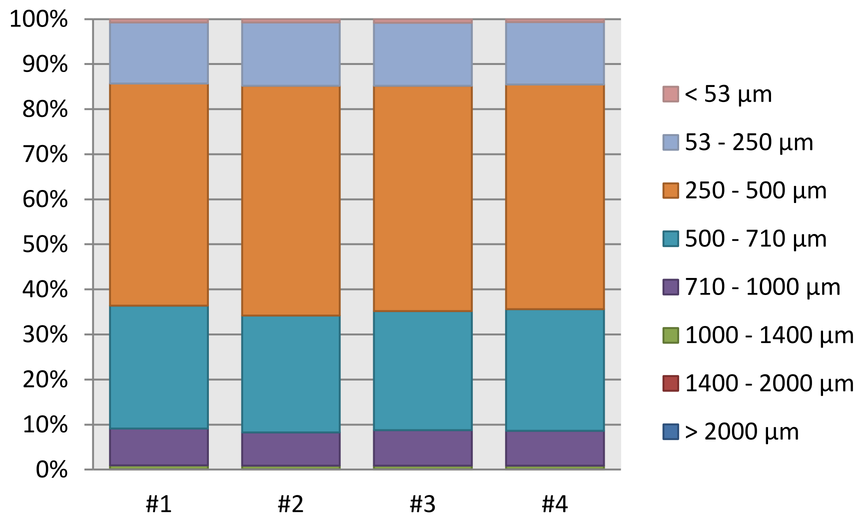

Figure A1. 1. Comparison between replicates for soil texture characterization.

Table A1. 12. Biochar aggregate size distribution in terms of mass percentage, replicates 1 and 2.

Particle size	Replicate	Mass		Fraction	Replicate	Mass		Fraction
		Sediment	Total after sieving			Sediment	Total after sieving	
		g		%		g		%
> 5000 µm	#1	2,15	14,37	14,96	#2	2,91	13,71	21,23
4000 - 5000 µm		1,57		10,93		1,41		10,28
3150 - 4000 µm		1,47		10,23		1,56		11,38
2000 - 3150 µm		2,46		17,12		2,23		16,27
200 - 2000 µm		5,77		40,15		4,81		35,08
50 - 200 µm		0,75		5,22		0,67		4,89
< 50 µm		0,20		1,39		0,12		0,88

Table A1. 13. Biochar aggregate size distribution in terms of mass percentage, replicates 3 and 4.

Particle size	Replicate	Mass		Fraction	Replicate	Mass		Fraction
		Sediment	Total after sieving			Sediment	Total after sieving	
		g		%		g		%
> 5000 µm	#3	2,14	11,11	19,26	#4	3,21	16,04	20,01
4000 - 5000 µm		1,5		13,50		1,88		11,72
3150 - 4000 µm		1,55		13,95		1,68		10,47
2000 - 3150 µm		2,69		24,21		2,64		16,45
200 - 2000 µm		2,26		20,34		5,4		33,66
50 - 200 µm		0,73		6,57		0,76		4,73
< 50 µm		0,24		2,16		0,47		2,93

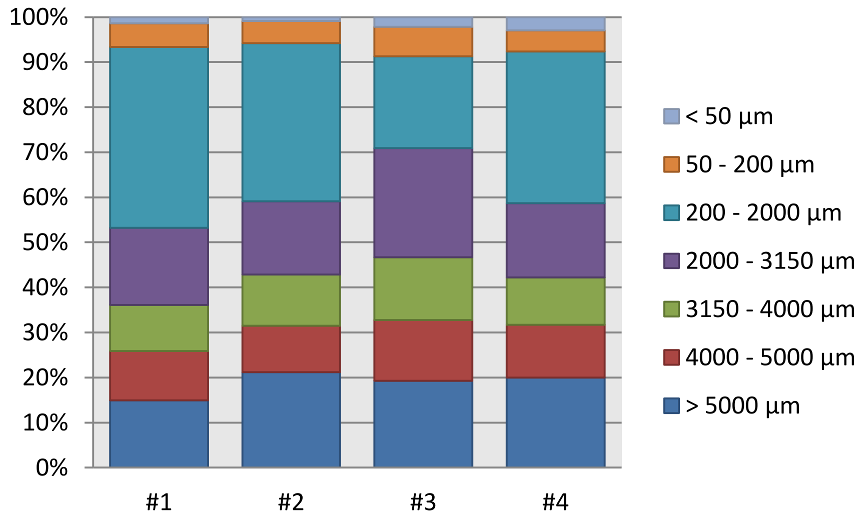

Figure A1. 2. Comparison between replicates for biochar particle size distribution.

Annex 2

In Annex 2 the information regarding the sample preparation is presented.

Table A2. 1. Moisture content determination for mixture and control at air-dried temperature.

Type of soils	Crucible	Mass				MC	Average MC	Average MC
		Crucible	Air-dried	Oven-dried	H_2O			
		[g]						[%]
Mixture	1	26,2215	35,2307	35,0487	0,1820	0,0206	0,0171	1,71
	2	26,7758	36,4919	36,3326	0,1593	0,0167		
	3	21,7317	36,0005	35,8016	0,1989	0,0141		
Control	1	25,6460	32,5169	32,5018	0,0151	0,0022	0,0021	0,21
	2	19,9369	27,1189	27,1039	0,0150	0,0021		
	3	24,1171	29,6996	29,6879	0,0117	0,0021		

Table A2. 2. Volume of water, in mL, to be added to reach the desired MC, from the air-dried condition.

Type of soils	Mass sample	Moisture content		Mass H_2O/mass air-dried sample	Mass H_2O target/mass air-dried sample	Mass H_2O			Volume H_2O added
		Air-dried	Target			Sample	Target	Added	
	[kg]					[kg]			[mL]
Mixture	5	0,0171	0,04	0,0168	0,0385	0,0841	0,1923	108,2452	108
		0,0171	0,08	0,0168	0,0741	0,0841	0,3704	286,3078	286
Control	6	0,0021	0,0171	0,0021	0,0168	0,0126	0,1009	88,3014	88
		0,0021	0,04	0,0021	0,0385	0,0126	0,2308	218,1956	218
		0,0021	0,08	0,0021	0,0741	0,0126	0,4444	431,8708	432

Table A2. 3. . Volume of water, in mL, to be added to biochar for reaching the desired MC, from the oven-dried condition.

Mass		Moisture content		Mass H_2O/mass air-dried sample	Mass H_2O target/mass air-dried sample	Mass H_2O			Volume H_2O added
Soil	**Biochar**	**Initial**	**Target**			**sample**	**target**	**added**	
[kg]						**[kg]**		**[g]**	**[mL]**
4,5	0,4525	0,0000	0,0026	0,0000	0,00259	0,0000	0,00117	1,17	1,17
4,617	0,4645	0,0000	0,0026	0,0000	0,00259	0,0000	0,00120	1,20	1,20
4,527	0,457	0,0000	0,0026	0,0000	0,00259	0,0000	0,00119	1,19	1,19

Annex 3

In annex 3, the information regarding the determination of the vertical profile above the soil surface is presented.

Table A3. 1. Determination of the wind velocity vertical profile for above the soil surface.

Atmospheric pressure [kPa]	Temperature [^oC]	Height above the tray [cm]	Height above the tunnel floor [cm]	Pressure difference [mm H_2O]	Velocity [m s^{-1}]
102,09	20,0	1	4,5	8,0	3,6
102,09	20,0	2	5,5	9,5	3,9
102,09	20,0	3	6,5	10,0	4,0
102,09	20,0	4	7,5	12,0	4,4
102,09	19,5	5	8,5	13,5	4,7
102,09	19,5	6	9,5	14,5	4,9
102,09	19,5	7	10,5	15,5	5,0
102,09	20,0	8	11,5	16,5	5,2
102,09	20,0	9	12,5	17,5	5,3
102,09	20,0	10	13,5	18,5	5,5
102,09	20,0	11	14,5	20,0	5,7
102,09	19,5	12	15,5	20,5	5,8
102,09	20,0	13	16,5	21,0	5,9
102,09	20,0	14	17,5	22,0	6,0
102,09	19,5	15	18,5	22,5	6,1
102,90	20,0	16	19,5	23,0	6,1
102,90	19,0	18	21,5	23,5	6,2
102,90	19,0	22	25,5	26,0	6,5
102,90	19,0	24	27,5	27,0	6,6
102,90	19,0	26	29,5	27,5	6,7
102,90	19,0	28	31,5	28,5	6,8
102,90	19,0	30	33,5	29,0	6,9
102,90	19,0	34	37,5	30,0	7,0
102,90	18,5	38	41,5	30,0	7,0
102,90	19,0	42	45,5	30,0	7,0

Annex 4

In annex 4 the mass of eroded sediments, in g, is given, between the different moisture contents.

Table A4. 1. Mass of biochar eroded sediment, in g, between the different MC.

Moisture content	Rep	Mass crucible	Mass crucible + non-oven-dried sediments	Mass crucible + oven-dried sediments	Mass non-oven-dried sediments	Sediments moisture content	Mass oven-dried sediments		Avg mass sediments	SD
		Mixture								
		[g]								
	1	29,3213	30,4144	30,3414	1,0931	7,1562	1,0201	1,0201		
	2	24,4286	25,4268	25,3621	0,9982	6,9309	0,9335	0,9335		
0,2%	3	26,3771	27,8604	27,7649	1,4833	6,8814	1,3878	1,3878	1,1393	0,1779
	4	24,0962	25,4071	25,3258	1,3109	6,6119	1,2296	1,2296		
	5	26,4553	27,6569	27,5806	1,2016	6,7804	1,1253	1,1253		
	1	49,9356	51,5503	51,4221	1,6147	8,6243	1,4865	1,4865		
	2	46,1457	47,5833	47,4718	1,4376	8,4081	1,3261	1,3261		
1,7%	3	35,9258	38,3964	38,1993	2,4706	8,6695	2,2735	2,2735	1,5284	0,4427
	4	41,7097	42,8979	42,8135	1,1882	7,6463	1,1038	1,1038		
	5	40,5949	42,1509	42,0469	1,5560	7,1625	1,4520	1,4520		
	1	27,3393	29,1811	29,0464	1,8418	7,8906	1,7071	1,7071		
	2	49,238	50,9359	50,8115	1,6979	7,9059	1,5735	1,5735		
4,0%	3	46,9148	48,6148	48,4848	1,7000	8,2803	1,5700	1,5700	1,4343	0,2649
	4	27,8457	29,1983	29,1021	1,3526	7,6568	1,2564	1,2564		
	5	21,4634	22,621	22,5278	1,1576	8,7561	1,0644	1,0644		
	1	22,4048	23,3461	23,2827	0,9413	7,2218	0,8779	0,8779		
	2	22,2359	23,0666	23,0064	0,8307	7,8131	0,7705	0,7705		
8,0%	3	24,9467	25,6709	25,6311	0,7242	5,8153	0,6844	0,6844	0,7641	0,0915
	4	23,9963	24,6979	24,6584	0,7016	5,9659	0,6621	0,6621		
	5	25,0979	25,9795	25,9233	0,8816	6,8088	0,8254	0,8254		

Table A4. 2. Mass of soil eroded sediment, in g, between the different MC.

		Control								
Moisture content	**Rep**	**Mass crucible**	**Mass crucible + non-oven-dried sediments**	**Mass crucible + oven-dried sediments**	**Mass non-oven-dried sediments**	**Sediments moisture content**	**Mass oven-dried sediments**		**Avg mass sediments**	**SD**
		[g]								
	1	18,653	18,7100	18,7058	0,0570	0,0795	0,0528	0,0528		
	2	24,5677	24,6098	24,6075	0,0421	0,0578	0,0398	0,0398		
0,2%	3	28,4964	28,5413	28,5381	0,0449	0,0767	0,0417	0,0417	0,0437	0,0109
	4	26,5544	26,5849	26,5829	0,0305	0,0702	0,0285	0,0285		
	5	27,0898	27,1473	27,1456	0,0575	0,0305	0,0558	0,0558		
	1	24,3038	24,3231	24,3221	0,0193	0,0546	0,0183	0,0183		
	2	23,3776	23,3939	23,3933	0,0163	0,0382	0,0157	0,0157		
1,7%	3	27,7298	27,7388	27,7384	0,0090	0,0465	0,0086	0,0086	0,0159	0,0073
	4	26,7194	26,7297	26,7293	0,0103	0,0404	0,0099	0,0099		
	5	25,6995	25,7276	25,7264	0,0281	0,0446	0,0269	0,0269		
	1	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000		
	2	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000		
4,0%	3	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
	4	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000		
	5	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000		
	1	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000		
	2	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000		
8,0%	3	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
	4	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000		
	5	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000		

Annex 5

In annex 5, there is a brief protocol on the method to prepare the soil and biochar samples.

Soil and biochar sample preparation protocol

1. Fill up the sample area with soil at a desired moisture content until it is levelled with the borders, then remove it and weigh it on a balance. This will be the mass of soil necessary for control samples. Add the amount of biochar to reach the desired biochar concentration and mix it up to have a homogeneous distribution.
2. Oven-dry the mixture at 105^{o}C for 24h and weigh it, after stabilizing for 1 hour in a desiccator. Lay the mixture in the same tray and level it the same way as in the beginning. Weigh the remains and subtract the value from the total to know how much mixture is needed.
3. Preparation of samples
4. Weigh the amount of soil for the control samples and biochar-amended soil necessary to have a desired concentration, putting each sample in a plastic bag labelled.
5. Store the bag in room at air-dried temperature for 1 day. Then, determine the moisture content of control and mixture at air-dried temperature.
6. After selecting the higher MC to be tested, add the volume of distilled water needed to reach those chosen values using a vaporizer from a spray bottle and, if possible, in a way that minimizes water losses on the bag surface.
7. Insert a setup of turbulence generators and floor roughness elements, in order to establish the atmospheric boundary layer. Measure the velocity with a pitot tube in a position upwind from the sample tray. The vertical profile for the wind velocity along the boundary layer should have been previously determined at three positions: upwind, above and downwind of the sample tray. Place the sample tray in the middle even with the tunnel floor or minimize the tray borders by using system of ramps with a slope of at least 7%.
8. Divide the sample tray with a wooden barrier so that the last 30 cm can be used to collect the particles that move due to the wind. Add the soil to the tray, levelling it with its borders and take a picture of the soil area before and after experiment. At the end, a picture should also be taken to the collecting area of the tray. Put the particles at a labelled small plastic bag.